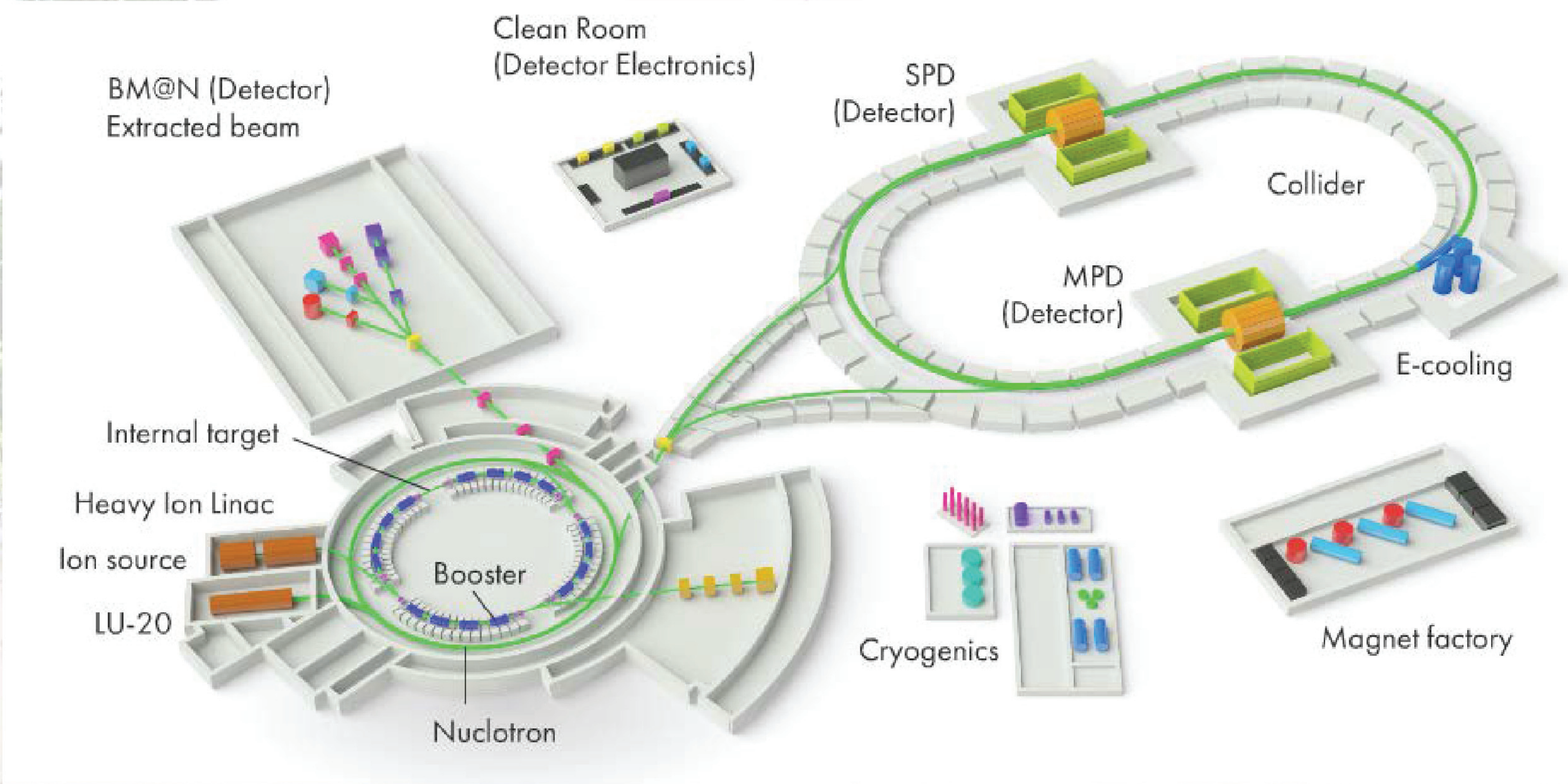
Ion Accelerators for Russian Mega-Science Projects

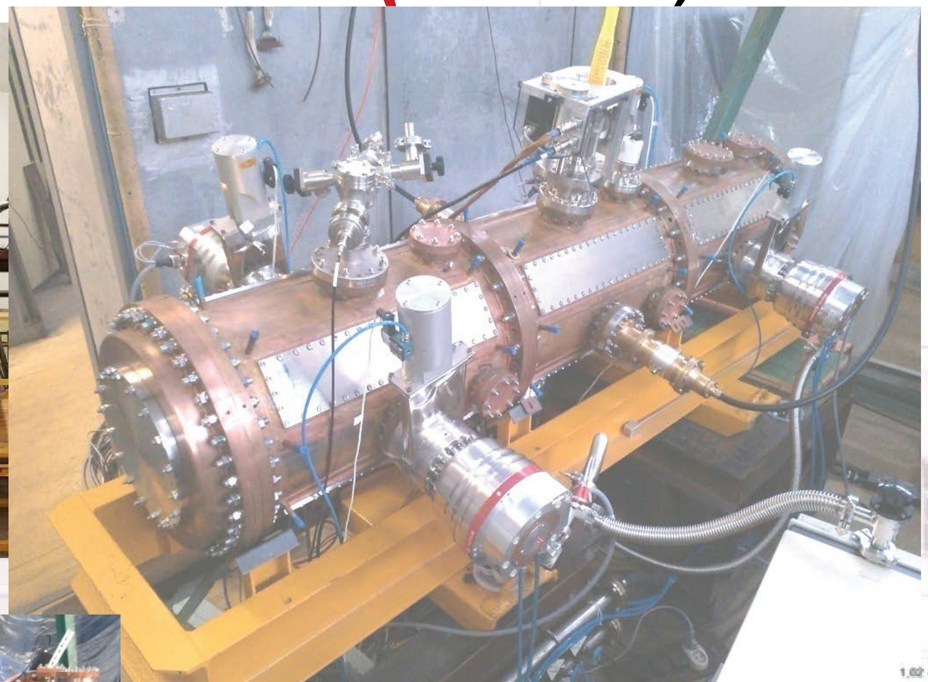
Timur Kulevoy

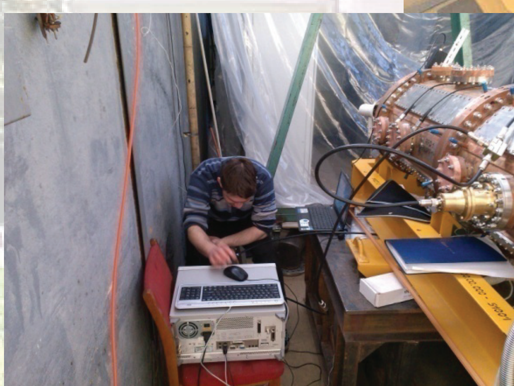
Nuclotron-based Ion Collider fAcility (NICA)

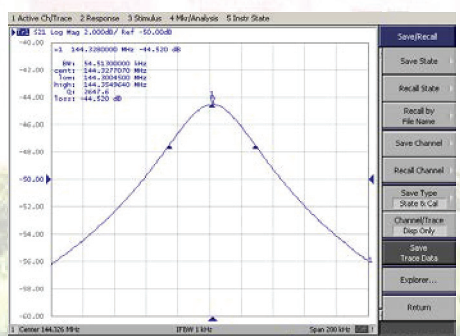


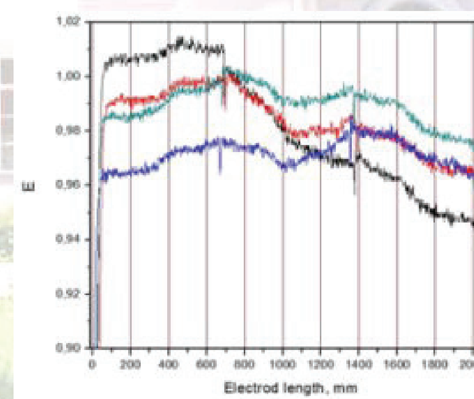
Nuclotron-based Ion Collider fAcility (NICA)

Nuclotron-based Ion Collider fAcility (NICA)

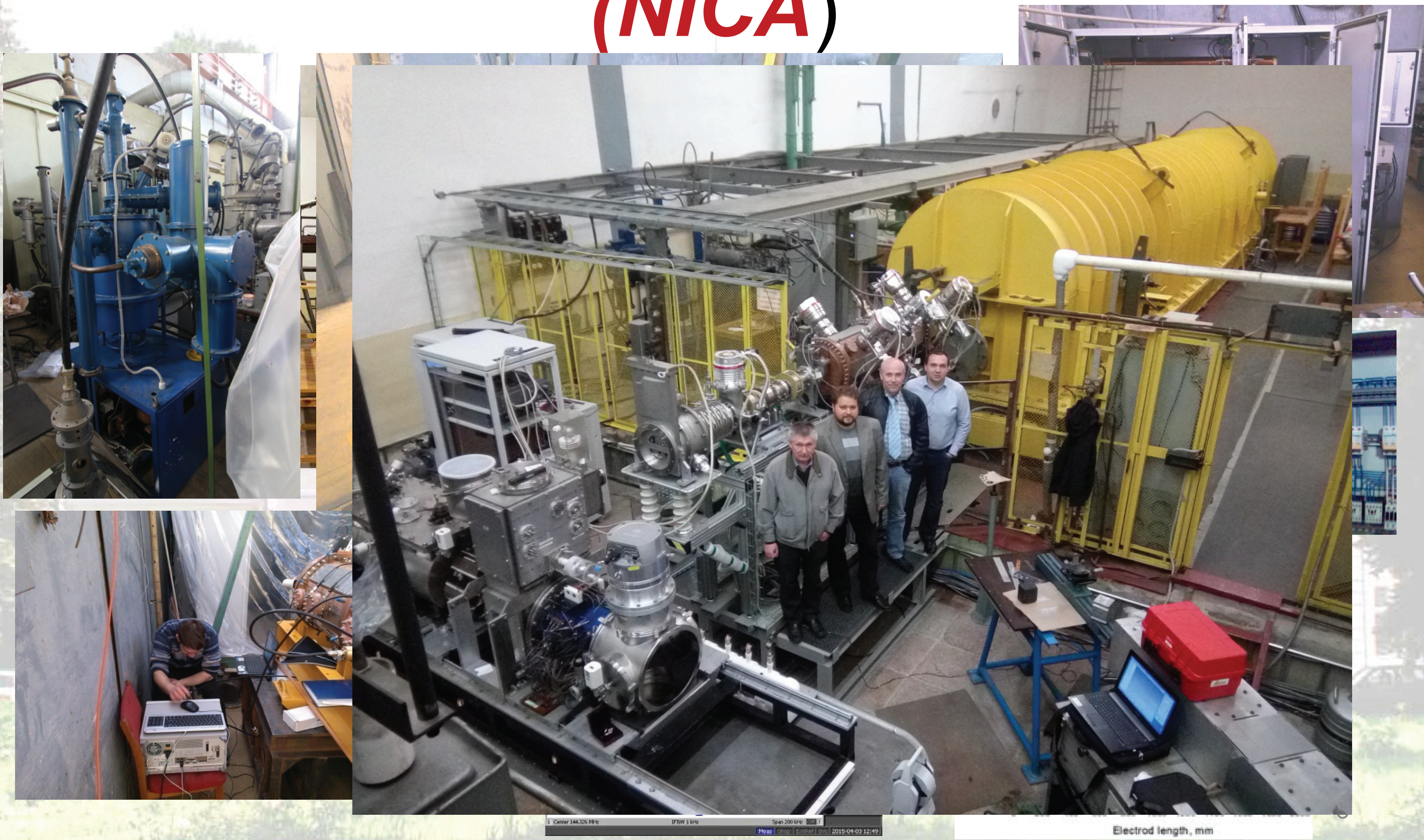








Nuclotron-based Ion Collider fAcility (NICA)



Nuclotron-based Ion Collider fAcility (NICA)

АЛЕКСАНДРОВ В.С.[3], АНДРЕЕВ В.А.[1], БАЛАБИН А.И.[1], БАРАБИН С.В.[1], БУТЕНКО А.В.[3], ГОВОРОВ А.И.[3], ГОЛОВЕНСКИЙ Б.В.[3], ГУСАРОВА М.А.[2], ДЮБКОВ В.С.[2], КЛЫКОВ К.А.[4], КОБЕЦ В.В.[3], КОВАЛЕНКО А.Д.[3], КОЗЛОВ А.В.[1], КОШЕЛЕВ В.А.[1], КРОПАЧЕВ Г.Н.[1], КУЙБИДА Р.П.[1], КУЗЬМИЧЕВ В.Г.[1], КУЛЕВОЙ Т.В.[1,2], ЛЕВТЕРОВ К.А.[3], ЛУКАШИН А.Ю.[1], ЛЯКИН Д.А.[1], МАМАЕВ И.В.[4], МАРТЫНОВ А.А.[1,3], МОНЧИНСКИЙ В.А.[3], НАУМЕНКО М.Ю.[4], ОРЛОВ А.Ю.[1], ОСТАШКОВ Г.Н.[4], ПЛАСТУН А.С.[1,2], ПОЛОЗОВ С.М.[2,1], САМОШИН А.В.[2], СЕЛЕЗНЕВ В.В.[3], СЕЛЕЗНЕВ Д.Н.[1], СИДОРИН А.О.[3], СИТНИКОВ А.Л.[1], СТАСЕВИЧ Ю.Б.[1], ТРУБНИКОВ Г.В.[3]

[1]*ГНЦ РФ ИТЭФ НИЦ «Курчатовский институт»*

[2]*Национальный исследовательский ядерный университет «МИФИ»*

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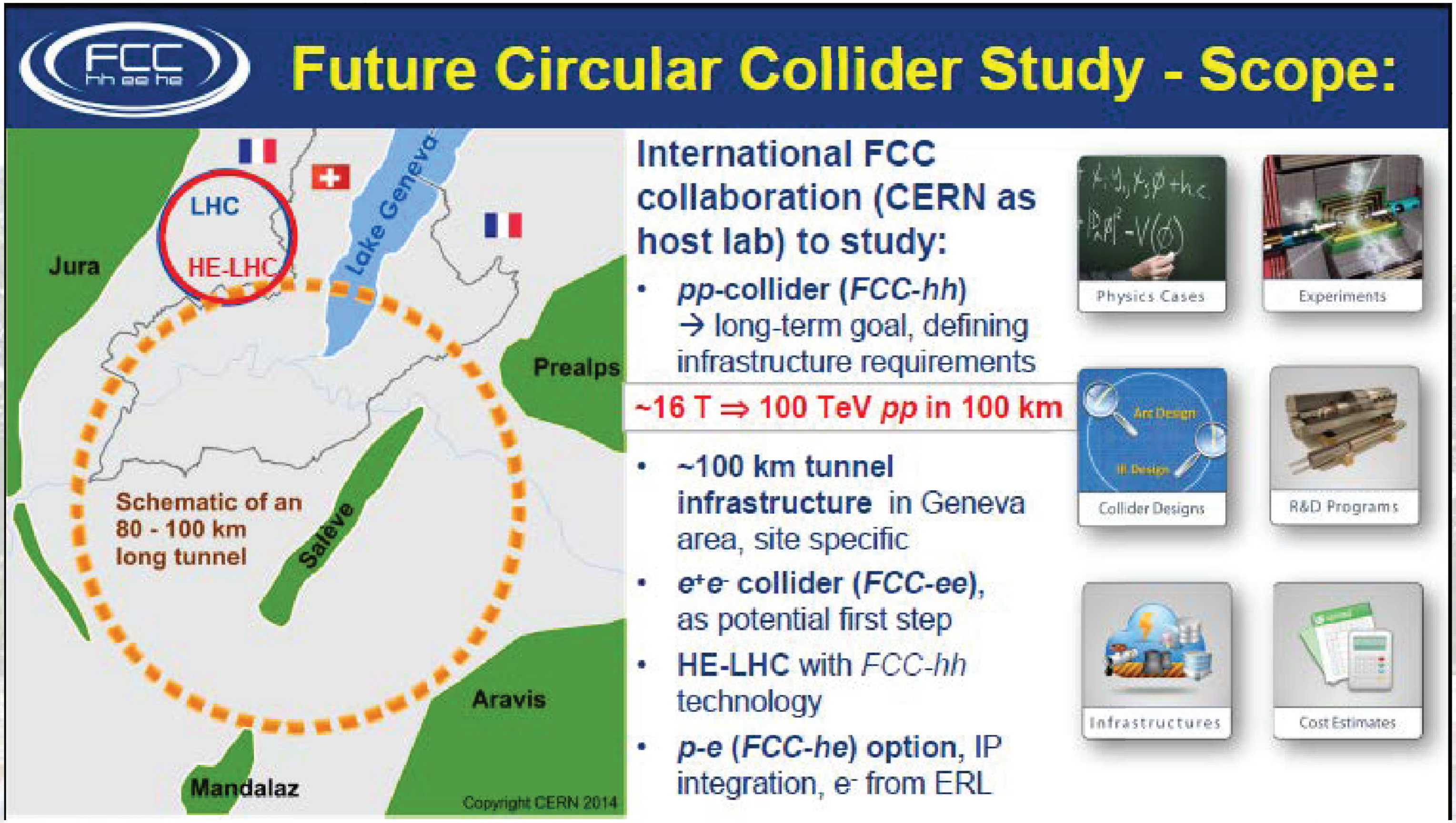
[4]*Российский Федеральный Ядерный Центр – Всероссийский научно-исследовательский институт технической физики имени*
академика Е.И. Забабахина,

HIGH ENERGY PHYSICS

HIGH ENERGY PHYSICS

HIGH ENERGY PHYSICS



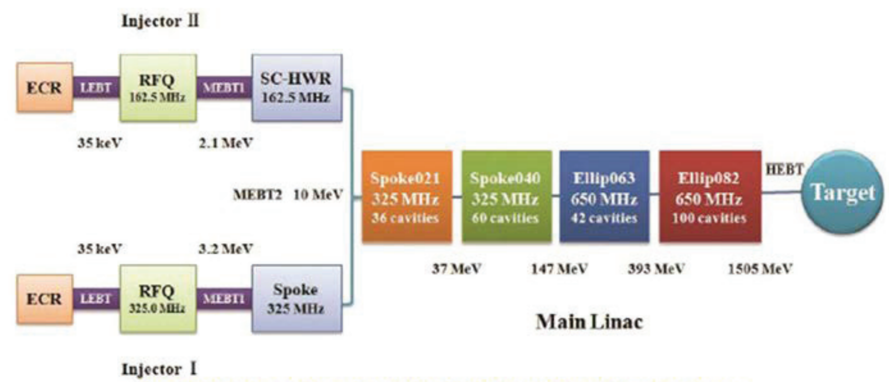
Future Circular Collider Study
Overview and Design Status
M. Benedikt and F. Zimmermann
gratefully acknowledging input from FCC coordination group, global FCC design study team and all other contributors

ADS

Accelerator Driven Systems

ADS
Accelerator Driven Systems

Chinese accelerating driven system (C-ADS), Huizhou, China

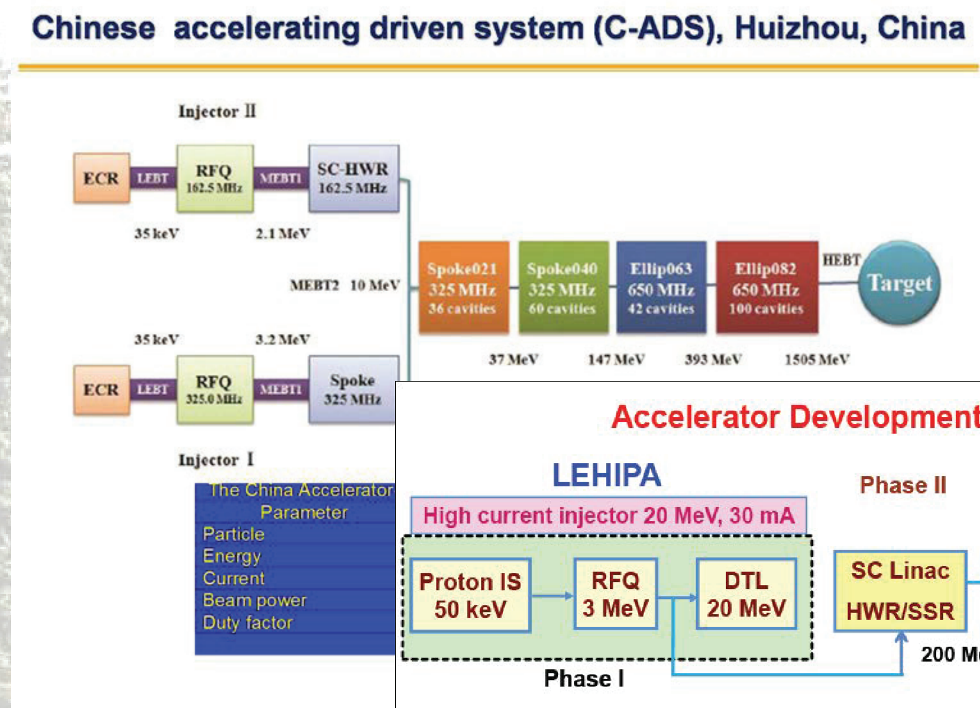


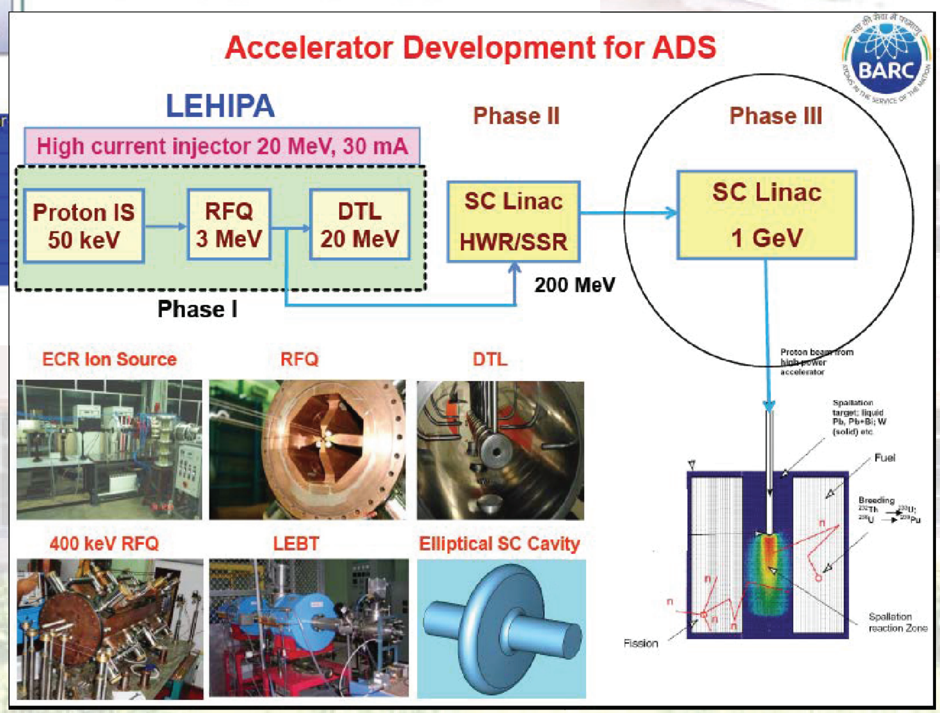
The China Accelerator-Driven Subcritical System Main Characteristics		
Parameter	Value	Unit
Particle	Proton	
Energy	1.5	GeV
Current	10	mA
Beam power	15	MW
Duty factor	100	%

Cavity Failures in C-ADS Injector-I, J. P. Dai et.al., IPAC17

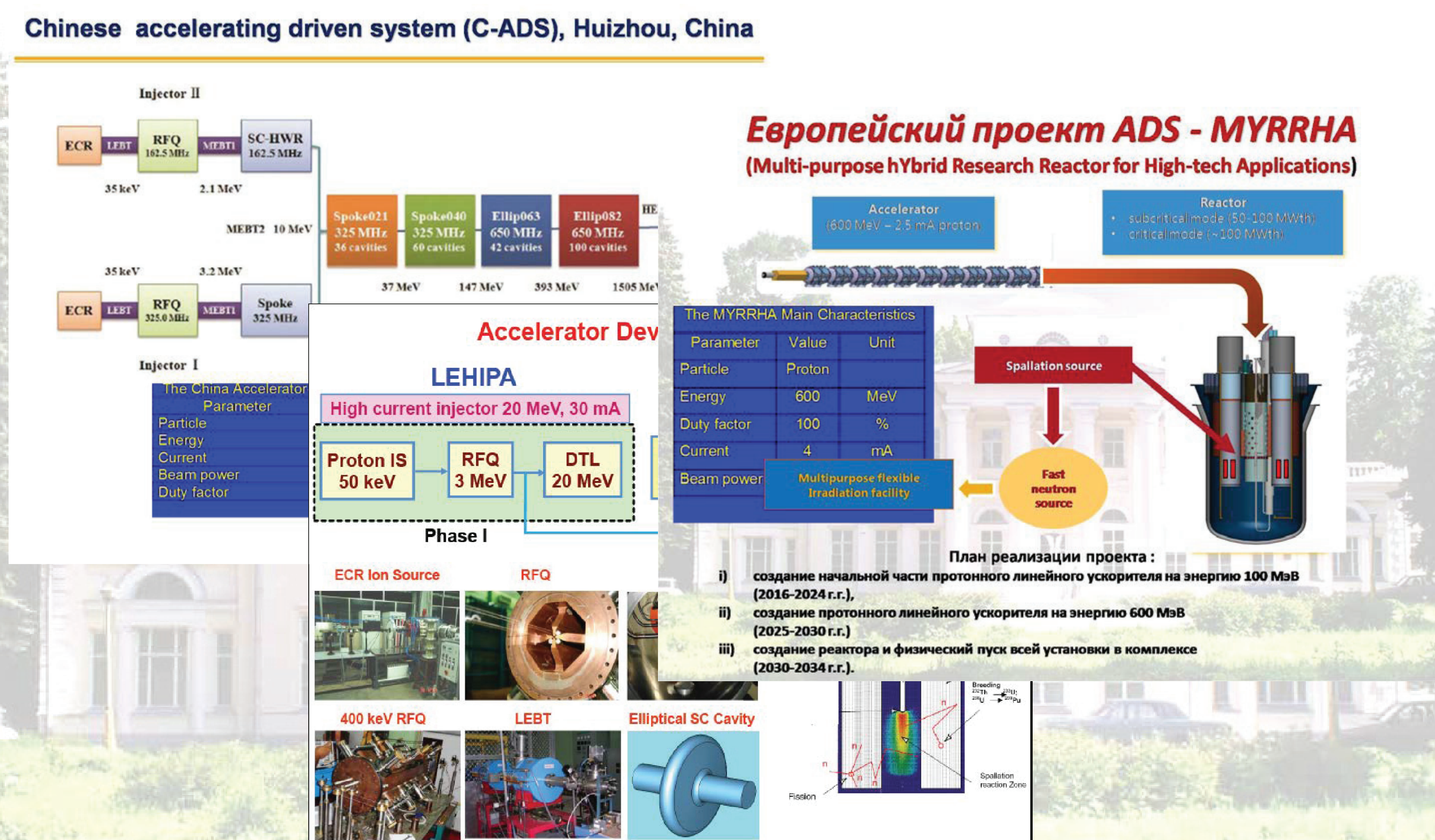
ADS

Accelerator Driven Systems





ADS
Accelerator Driven Systems

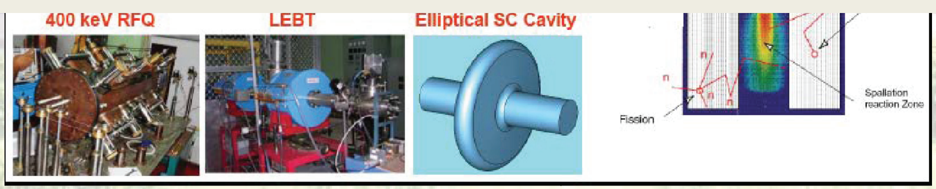


ADS
Accelerator Driven Systems

Chinese accelerating driven system (C-ADS), Huizhou, China

Европейский проект ADS - MYRRHA

- **предпочтительный тип ускорителя в качестве ADS-драйвера – протонный линейный ускоритель;**
- **энергия ускорителя – 1 ГэВ;**
- **интенсивность протонного пучка – 10 мА (с необходимостью изучения возможности использования дейтронного пучка D^+, что даст двукратное преимущество);**
- **стабильность – количество «срывов» пучка при индустриальном применении ADS системы не должно превышать 3 в месяц.**



ADS

ADS Technology Readiness Assessment

		Transmutation Demonstration	Industrial-Scale Transmutation	Power Generation
Front-End System	Performance	Green	Green	Green
	Reliability	Yellow	Yellow	Red
Accelerating System	RF Structure Development and Performance	Green	Green	Green
	Linac Cost Optimization	Green	Yellow	Yellow
	Reliability	Yellow	Yellow	Yellow
RF Plant	Performance	Green	Green	Green
	Cost Optimization	Green	Yellow	Yellow
	Reliability	Yellow	Yellow	Red
Beam Delivery	Performance	Green	Green	Green
Target Systems	Performance	Green	Yellow	Yellow
	Reliability	Yellow	Yellow	Yellow
Instrumentation and Control	Performance	Green	Yellow	Yellow
Beam Dynamics	Emittance/halo growth/beamloss	Green	Yellow	Yellow
	Lattice design	Green	Yellow	Yellow
Reliability	Rapid SCL Fault Recovery	Yellow	Red	Red
	System Reliability Engineering Analysis	Yellow	Red	Red

Green: “ready”, Yellow: “may be ready, but demonstration or further analysis is required”, Red: “more development is required”.

S. Henderson

Fermilab

ADS

ADS Technology Readiness Assessment

РЕАКТОР НА БЫСТРЫХ НЕЙТРОНАХ

		Transmutation Demonstration	Industrial-Scale Transmutation	Power Generation
Front-End System	Performance	Green	Green	Green
[illegible]	Reliability	Yellow	Yellow	Red
[illegible]	RF Structure Development [illegible]d Performance	Green	Green	Green
[illegible]	[illegible]ptimization	Green	Yellow	Yellow
[illegible]	[illegible]	Yellow	Yellow	Yellow
RF Plant	[illegible]	Green	Green	Green
	Cost Opti[illegible]	Green	Yellow	Yellow
	Reliability	Yellow	Yellow	Red
Beam Delivery	Performance	[illegible]	Green	Green
Target Systems	Performance	Green	Yellow	Yellow
	Reliability	Yellow	[illegible]	Yellow
Instrumentation and Control	Performance	Green	Yellow	Yellow
Beam Dynamics	Emittance/halo growth/beamloss	Green	Yellow	Yellow
	Lattice design	Green	Yellow	Yellow
Reliability	Rapid SCL Fault Recovery	Yellow	Red	Red
	System Reliability Engineering Analysis	Yellow	Red	Red

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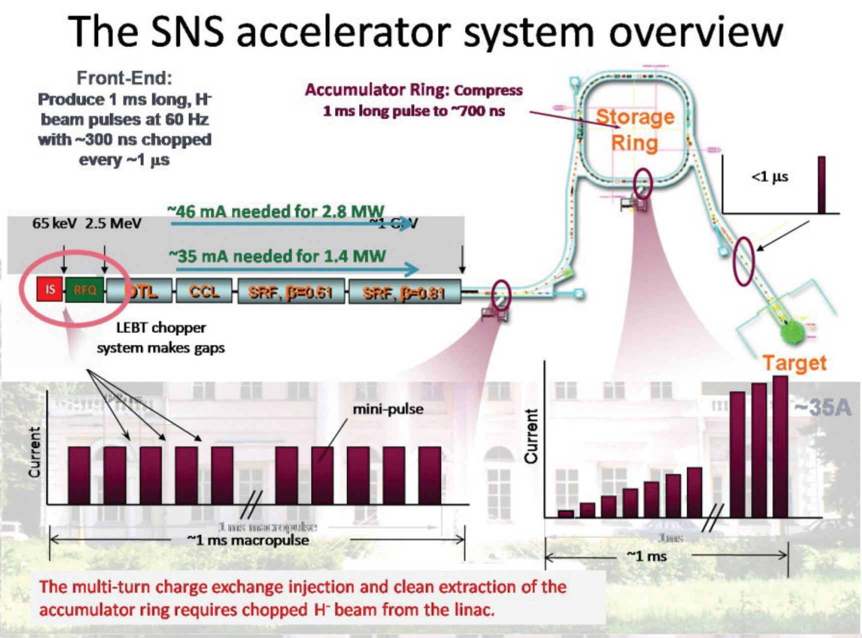
S. Henderson

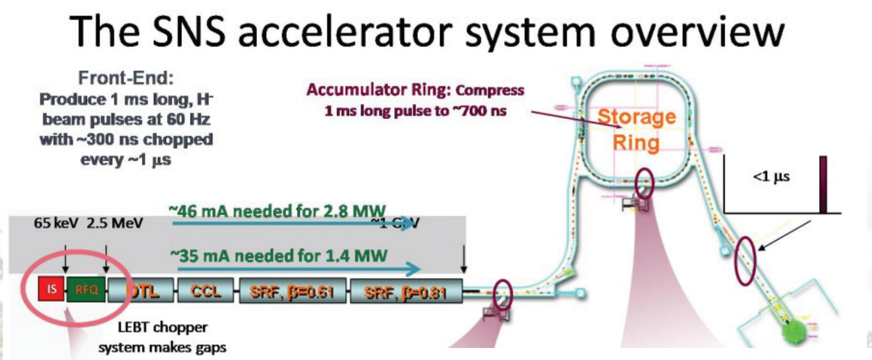
Fermilab

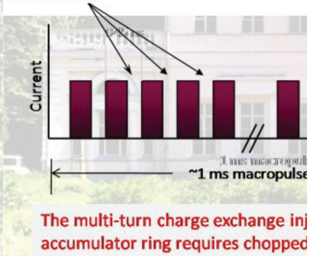
Spallation Source

Spallation Source



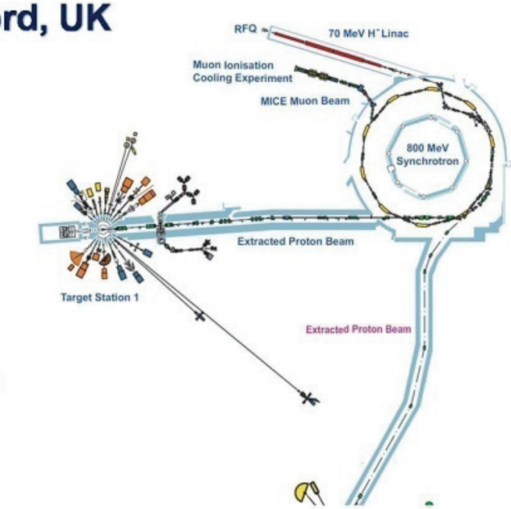
Spallation Source

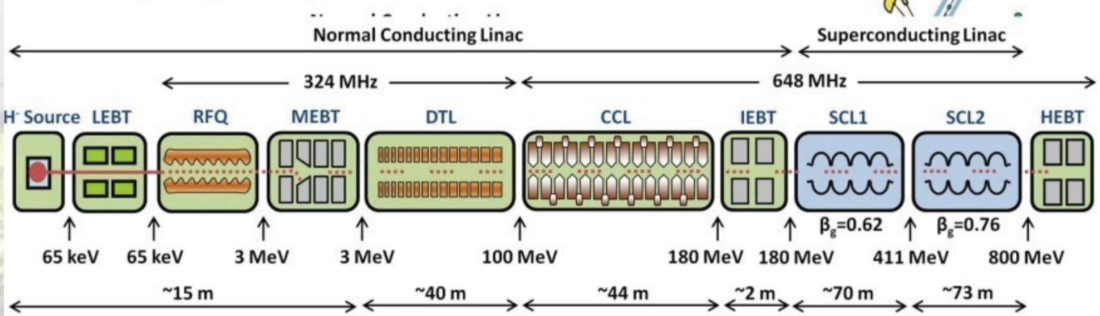




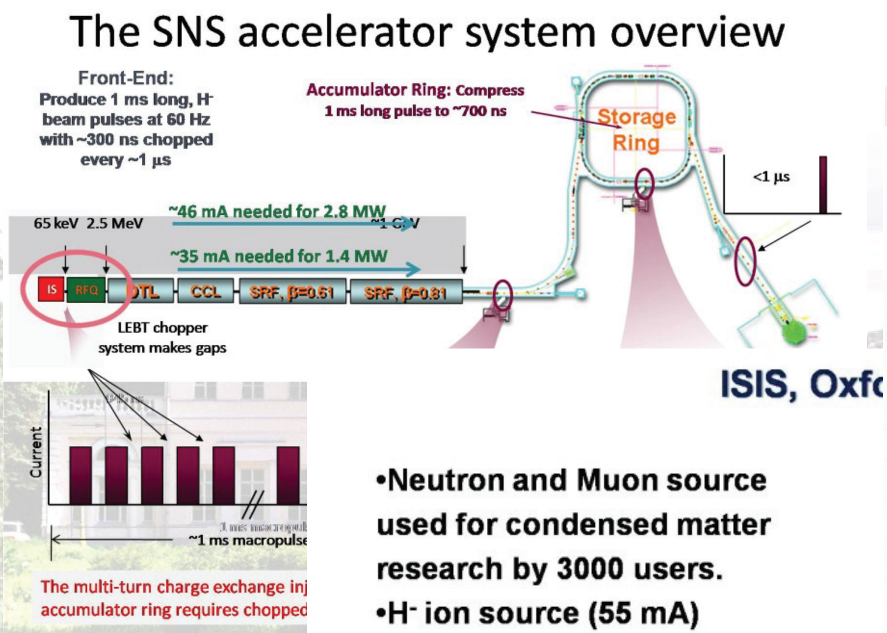
ISIS, Oxford, UK

- Neutron and Muon source used for condensed matter research by 3000 users.
- H⁻ ion source (55 mA)
- 665 keV RFQ (35 mA)
- 70 MeV linac (26 mA)
- 800 MeV 50 Hz, RCS ($2.8x10^{13}$ ppp)
- Target 1 + Muon target (140 kW)
- Target 2 (36 kW)





Spallation Source



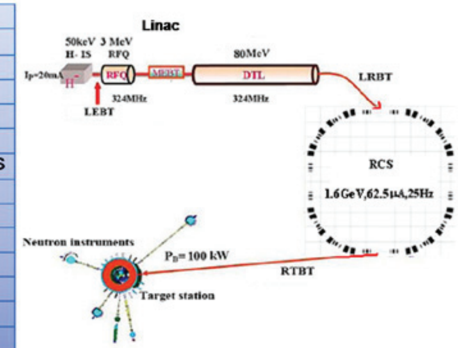
ISIS, Oxf

- Neutron and Muon source used for condensed matter research by 3000 users.
- H^- ion source (55 mA)
- 665 keV RFQ (35 mA)
- 70 MeV linac (26 mA)
- 800 MeV 50 Hz, RCS (2.8×10^{13} ppp)
- Target 1 + Muon target (140 kW)
- Target 2 (36 kW)

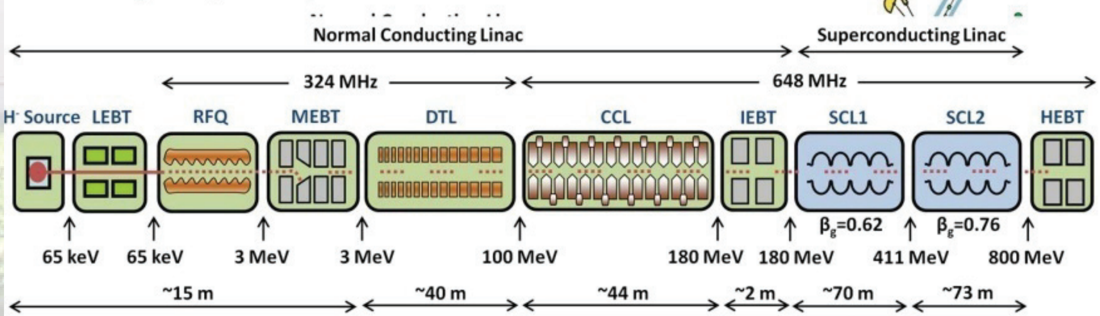
Project Design

- The phase-I CSNS facility consists of an 80-MeV H^- linac, a 1.6-GeV rapid cycling synchrotron(RCS), beam transport lines, a target station, and 3 instruments.

Project Phase	I	II
Beam Power on target [kW]	100	500
Proton energy [GeV]	1.6	1.6
Average beam current [μA]	62.5	312.5
Pulse repetition rate [Hz]	25	25
Linac energy [MeV]	80	300
Linac type	DTL	+Spoke/PIMS
Linac RF frequency [MHz]	324	324
Macropulse. ave current [mA]	15	40
Macropulse duty factor	1.0	1.7
RCS circumference [m]	228	228
RCS harmonic number	2	2
RCS Acceptance [πmm-mrad]	540	540
Target	1	1
Spectrometers	3	20

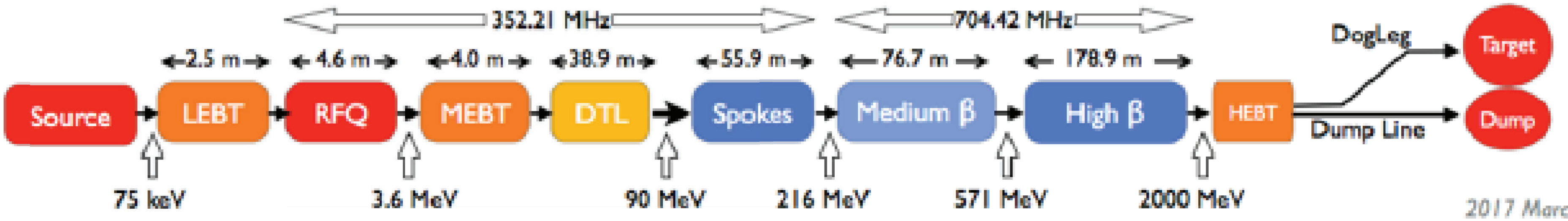


The first high-energy high-intensity proton accelerator in China



Linac Lattice and power levels

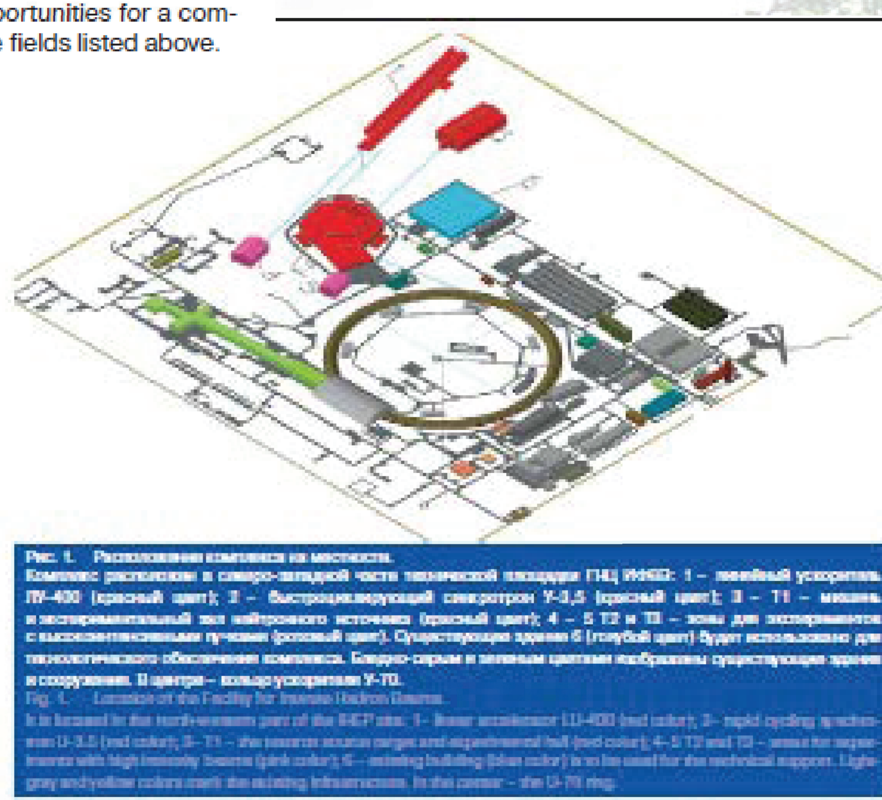
EUROPEAN SPALLATION SOURCE



	Energy (MeV)	Frequency /MHz	No. of Cavities	Temp / K	RF power required /kW	RF source	RF power specified /kW
Source	0.075	-	0	~300	–		
LEBT	0.075	-	0	~300	–		
RFQ	3.6	352.21	1	~300	1600	Klystron	3000
MEBT	3.6	352.21	3	~300	20	SSPA	35
DTL	90	352.21	5	~300	2200	Klystron	3000
Spoke	220	352.21	26 (2/CM)	~2	330	Tetrode	450
Medium β	570	704.42	36 (4/CM)	~2	870	Klystron	1500
High β	2000	704.42	84 (4/CM)	~2	1100	Klystron/IOT	1500/1200
HEBT	2000	–	0	~300	–		

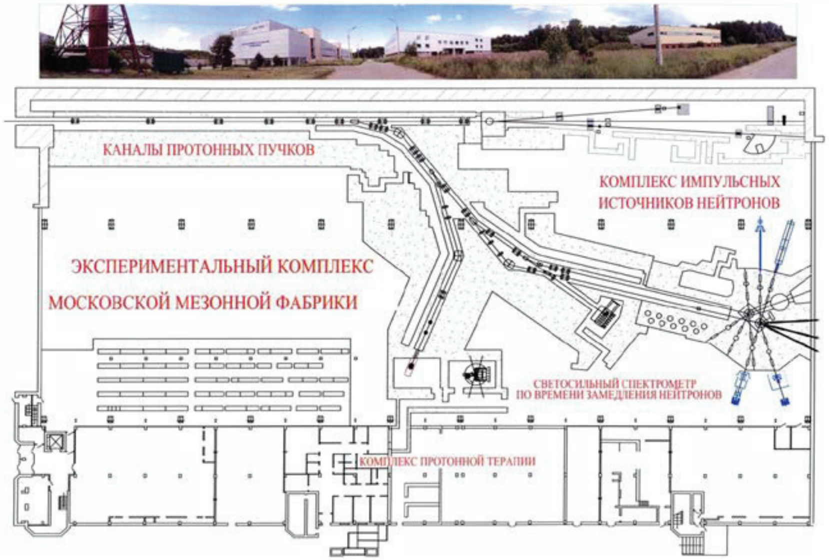
Spallation Source

The OMEGA Project also foresees construction of the pulsed spallation neutron source utilizing the 3.5 GeV and 1.1 MW proton beam (the study of biological structures, nanostructures, substances, materials, objects). These features of the neutron studies make The OMEGA Project complimentary to the synchrotron radiation sources thus providing unique opportunities for a comprehensive research in the science fields listed above.

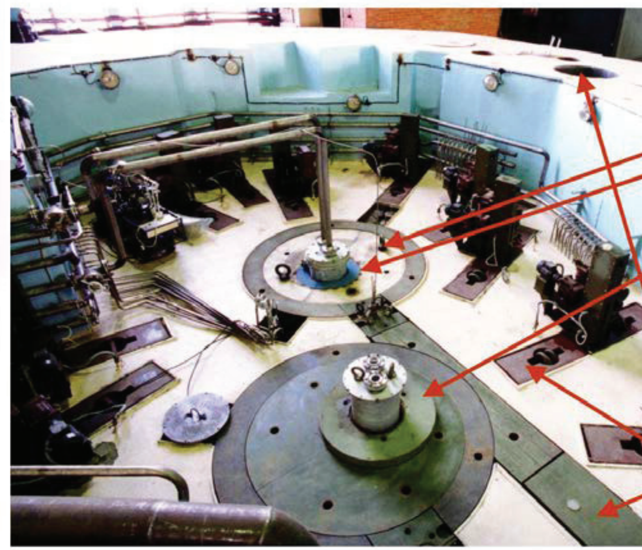


Spallation Source

Экспериментальный комплекс ИЯИ РАН в г. Троицке



Источник нейтронов ИН-06

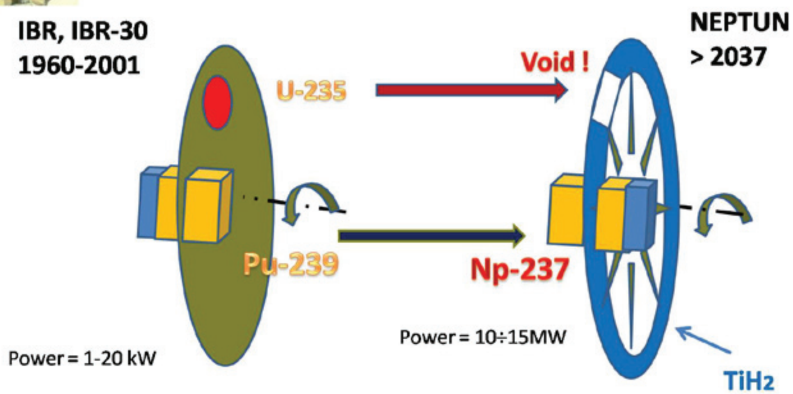


Фотография центральной верхней части комплекса источников нейтронов:
1 - бокс импульсного источника нейтронов,
2 - верхняя часть мишенного модуля.
3 – бокс для демонстрационного стенда (ADS), холодный источник (?),
4 - вертикальные проходки для установки дополнительного экспериментального оборудования,
5 - нейтроноводы
6 - стальная защита протонных пучков.

9

Spallation Source

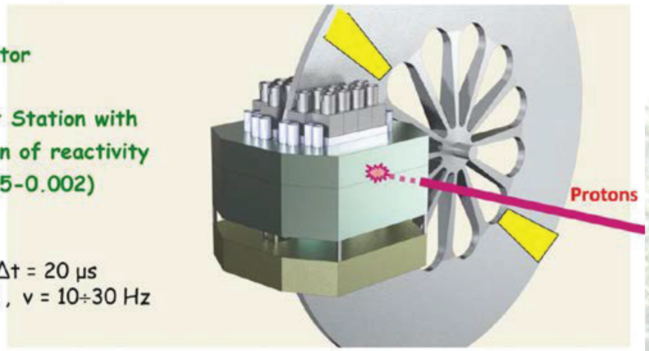
Superbooster NEPTUN



Evolution of IBR pulsing reactor (D.I.Blokhintse
NEPTUN (the pulsing subcritical reactor driven by

Superbooster NEPTUN

Linear p-Accelerator
+
Multiplying Target Station with periodic modulation of reactivity (subcriticality 0.05-0.002)



Ep =1.2 GeV, Δt = 20 μs
I max = 50 mA , ν = 10÷30 Hz
W ≤ 100 kW

Multiplying target:
Modulation of reactivity
Neptunium subcritical system
≤ 200-300 μs
e 20-30 μs

W = 10-15 MW

KoM-2018/7

Dubna Neutron Source of the 4-th Generation (DNS-IV)

Superbooster NEPTUN – Conceptual Design Report

Road Map (PAC Jan 2017: JINR E3-2017-12)

Activity	2015 – 17	2018 – 20	2021 – 23	2024 – 26	2027 – 32	2032 – 35
Conceptual research	2015 – 17					
Technical study		2018 – 20				
R & D			2021 – 23			
Engineering design				2024 – 26		
Construction					2027 – 32	
Commissioning						2032 – 35

PAC: Jan, June 2017, Jan 2018

JINR P13-2016-90 (Phys.Part.Nucl.Lett., 2017)

JINR E3-2017-12 (2017)

JINR P13-2017-57 (At. Energy, 2018)

Surface: Synchr.&Neutron Res. (2018)

Int. Conf. on IBR-2 Research (Dubna 2017)

Seminars: NRC "Kurchatov Institute"

Dollezhal R&D Institute of Power Engineering

Budapest Neutron Center

15 June 2018 at 15.00 Kick-off-Meeting of the WG of the JINR IWG on Strategy

Reactor complex PIK

Production of Radioactive Beams

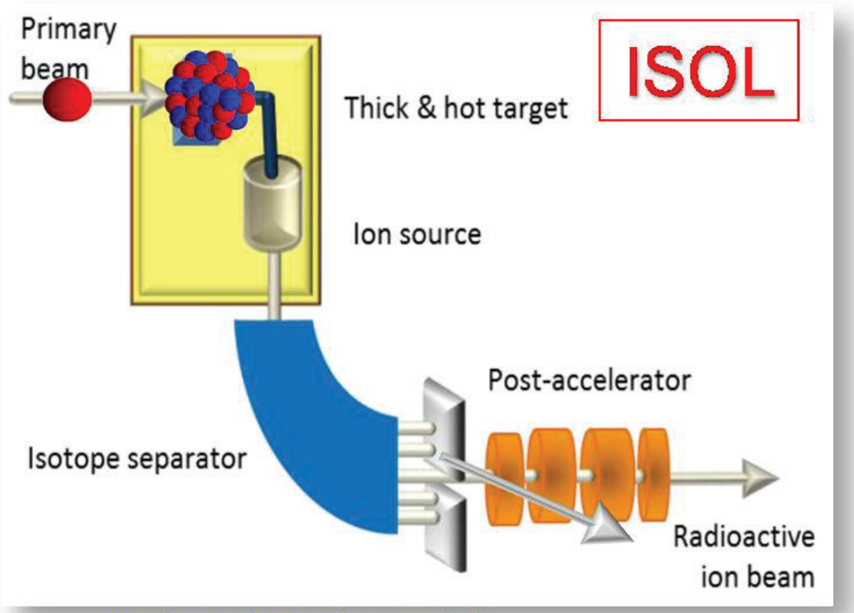
- Radioactive Ion Beams are produced using two complementary ways

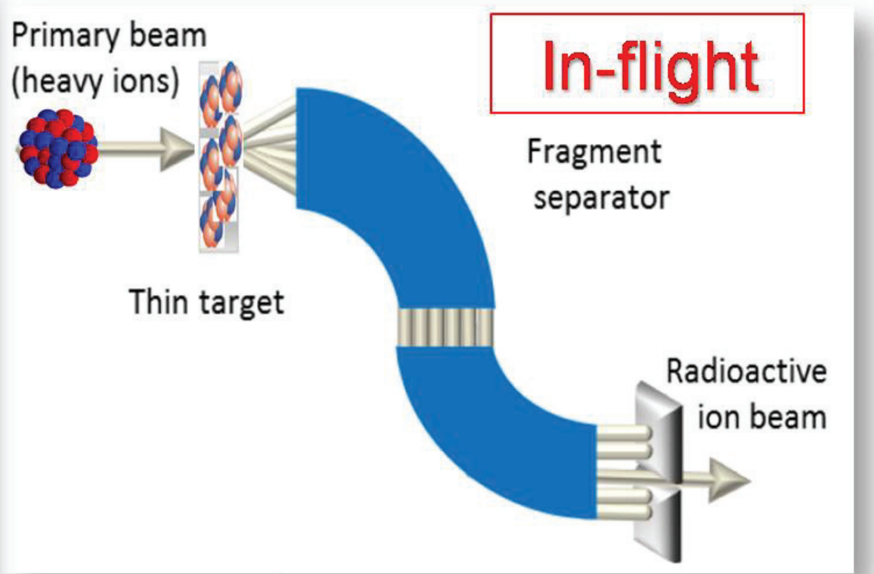
Isotope Separator On Line method (ISOL):

✓ low/medium energy, high quality beams (phase space)

In-flight method:

✓ high energy, short lived (μs)





Tailored made nuclei
Extraction time: ms – s
Well defined beam optics

Fast production
Many nuclei at the same time
Mapping region

21

Maria J. G. Borge
ISOLDE-PH, CERN
(Isotope Separator On-Line)

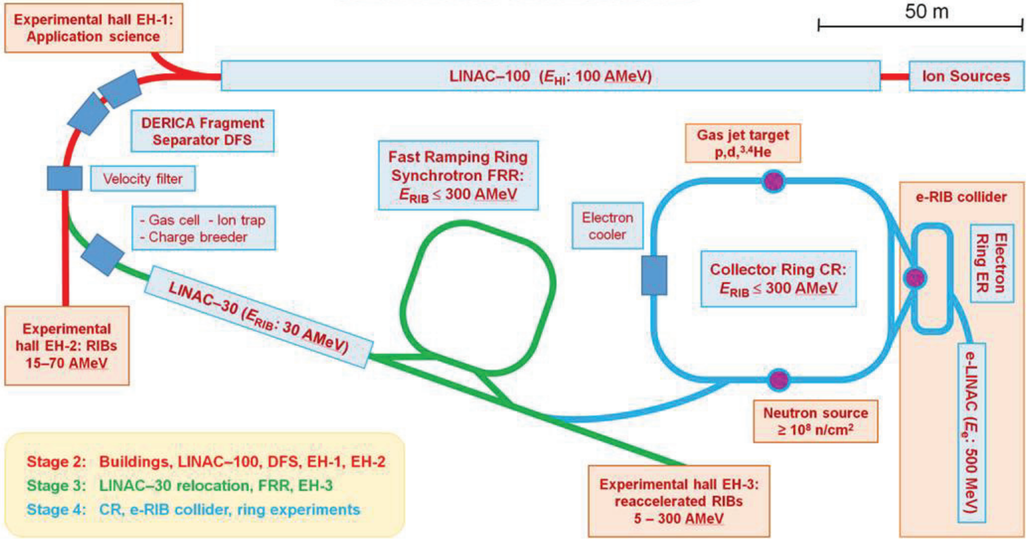
DERICA

Leonid Grigorenko

Flerov Laboratory of Nuclear Reactions, JINR, Dubna

Perspective plan of RIB research at JINR

Dubna Electron-Radioactive Isotope Collider fAcility DERICA



http://aculina.jinr.ru/derica.php

Discussion at FLNR, 27 August 2018

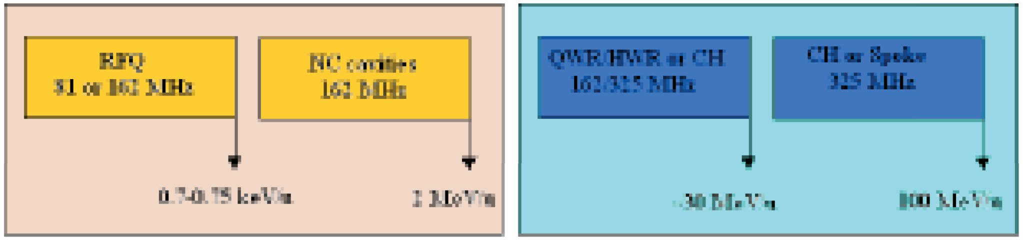
LINAC-100 concept

By teams led by T.V. Kulevoy (ITEPh) and S.M. Polozov (MEPhI)

Minimal primary beams

Ion	A/Z	I, pμA
$^{11}B^{2+}$	5.5	10 and more
$^{18}O^{3+}$	6.0	10 and more
$^{20,22}Ne^{4+}$	5.5	8 and more
$^{32,36}S^{6+}$	6.0	5 and more
$^{36}Ar^{6+}$	6.0	5 and more
$^{40,48}Ca^{7+}$	6.0	5 and more
$^{58,64}Ni^{11+}$	5.8	5 and more
$^{86}Kr^{15+}$	5.7	5
$^{132}Xe^{22+}$	6.0	5
$^{160}Gd^{27+}$	5.9	5
$^{209}Bi^{37+}$	5.65	4
$^{238}U^{40+}$	5.95	~ 0.8*

Normal conducting + SC parts



Normal conducting = RFQ + DTL

DERICA

$A/Z \leq 6.5$

Input current=1 mA

Input transverse emittance ε=1 π·mm·mrad

E_{smax}=1.5 Kp

V_h / ε =10

RFQ & MEBT& DTL (L=22 m)

RFQ : **f=40.625 MHz**; W=0.011 ÷ 0.5 MeV/u; L=10 m
MEBT: **f=81.25 MHz**; W=0.5 ÷ 0.5 MeV/u; L=0.5 m
DTL : **f=81.25 MHz**; W=0.5 ÷ 2.1 MeV/u; L=11.5 m

Layout of NC (normal conduction) linac

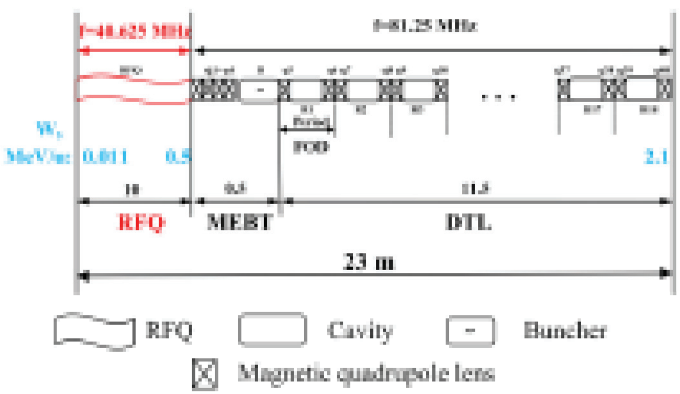
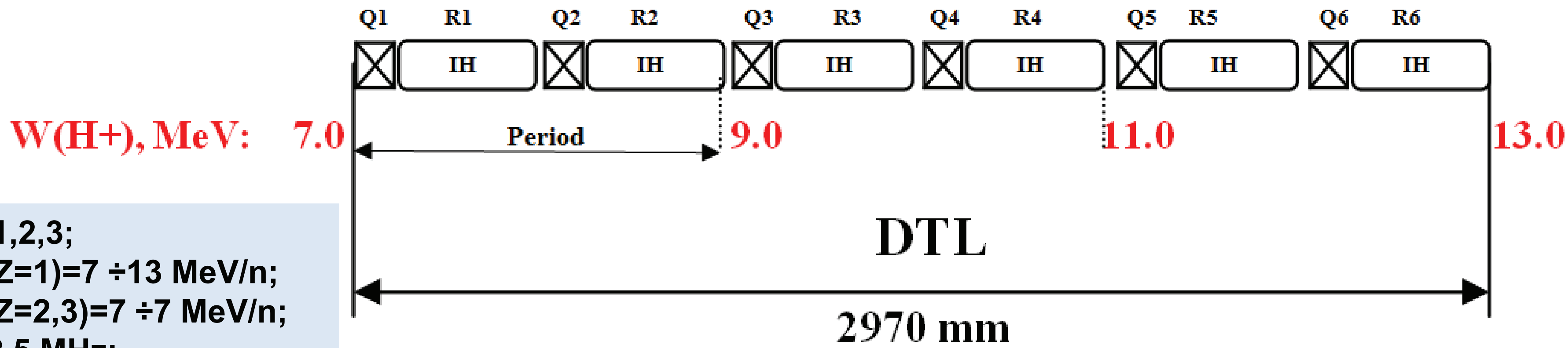
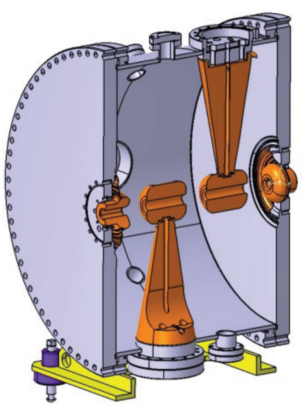


Схема канала DTL для нового инжектора проекта NICA

(предварительные оценки)



- A/Z=1,2,3;
- W(A/Z=1)=7 ÷13 MeV/n;
- W(A/Z=2,3)=7 ÷7 MeV/n;
- f=162.5 MHz;
- E_{smax}=1.8 Kp;
- Transmission=100%;



Z/A=1 W=7 - 13 MeV

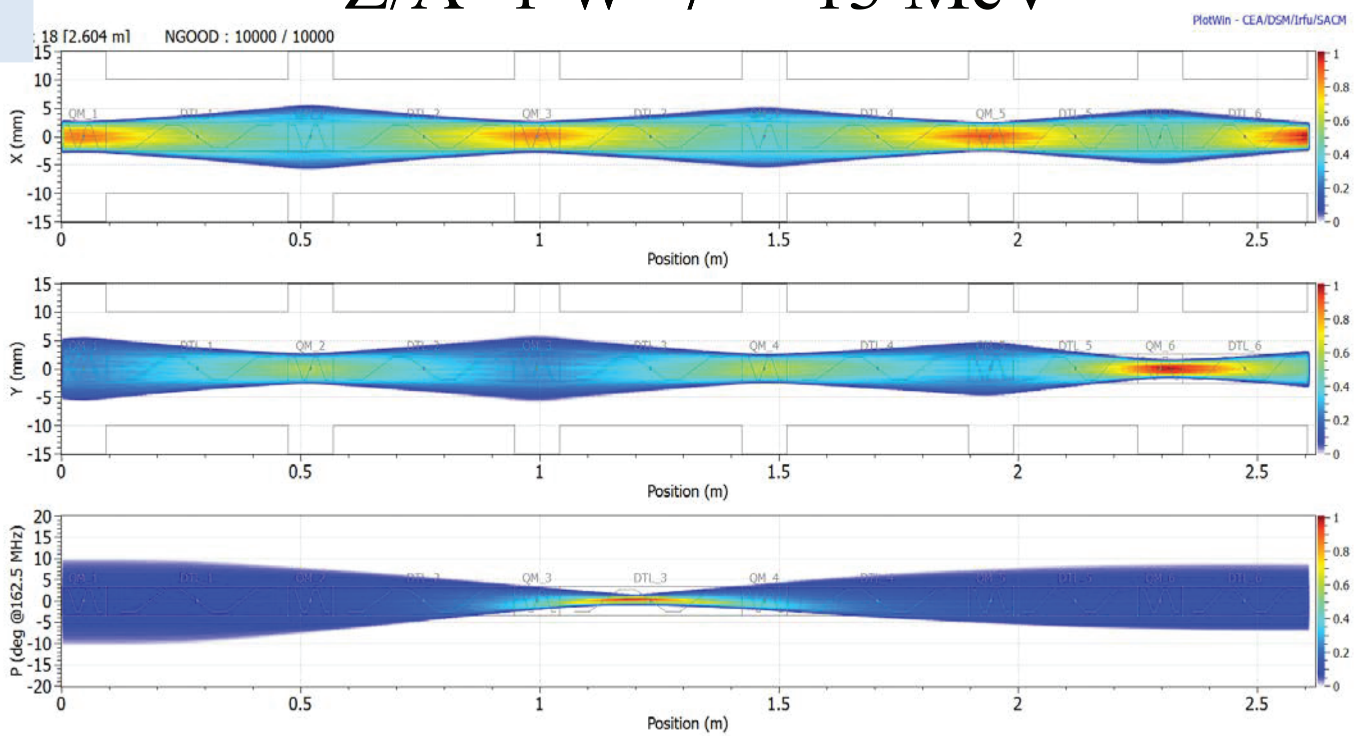
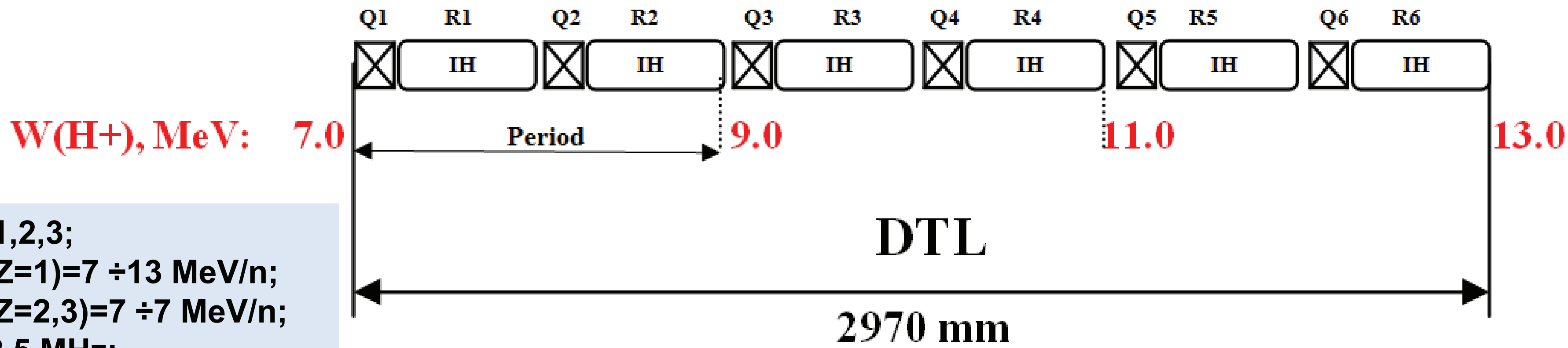


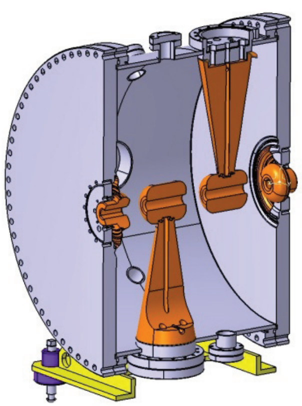
Схема канала DTL для нового инжектора проекта NICA

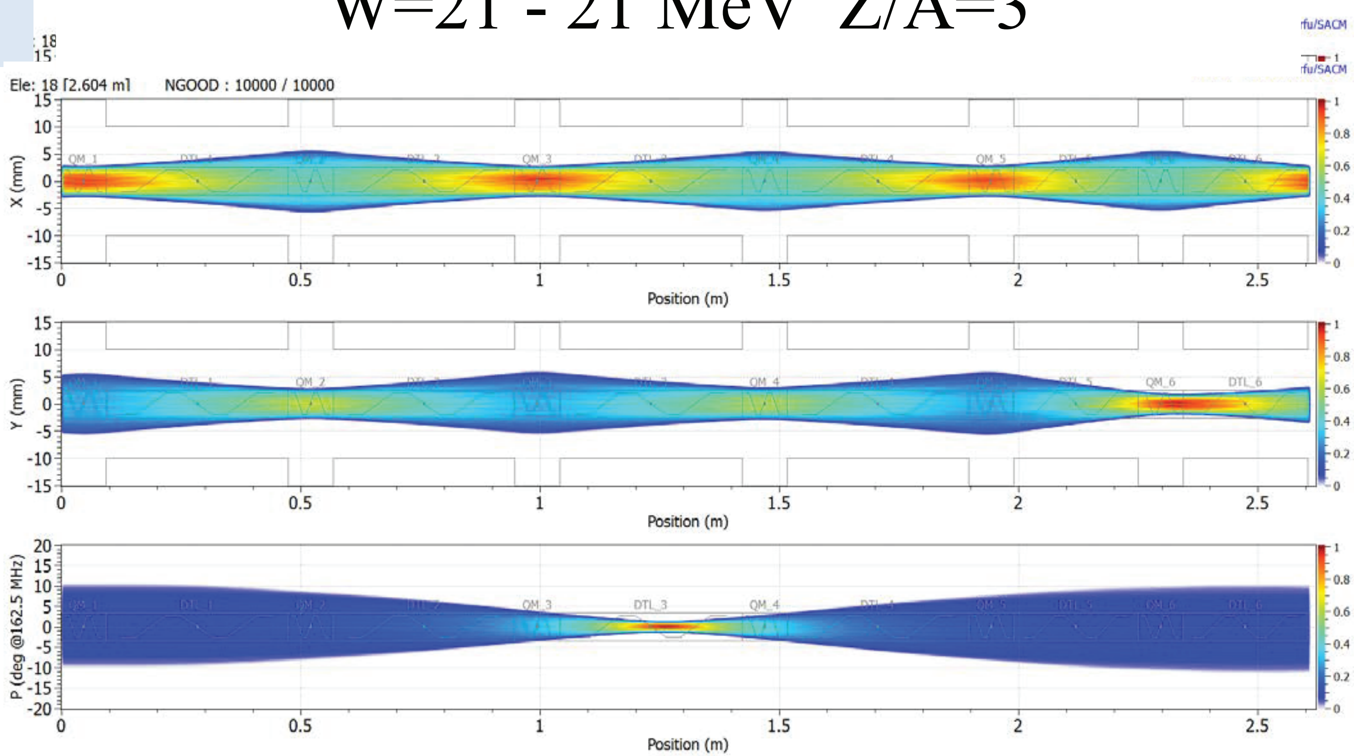
(предварительные оценки)



- A/Z=1,2,3;
- W(A/Z=1)=7 ÷13 MeV/n;
- W(A/Z=2,3)=7 ÷7 MeV/n;
- f=162.5 MHz;
- E_{smax}=1.8 Kp;
- Transmission=100%;

W=21 - 21 MeV Z/A=3





Что потребуется для мега-сайенс проекта?

- Ионный источник, генерирующий пучок протонов/ионов в режиме близком к непрерывному, с большим ресурсом работы (большим временем жизни)
- Нормально проводящие ускоряющие структуры, работающие в режиме cw или в режиме с малой скважностью. В первую очередь RFQ.
- Использование сверхпроводящих структур. Тенденция к началу их использования как можно с меньших энергий. На сегодня разумной переходной энергией выглядит энергия около 3 – 3.5 МэВ/н.
- Использование для ВЧ питания твердотельных усилителей ВЧ мощности.

Технологии создания линейного ускорителя в России

	Разработки	Опытные образцы	Серийная технология	Обладатели компетенций/ Участвующие в зарубежных проектах
Расчет динамики, проектирование	да	да	да	ИТЭФ, МИФИ, МРТИ
Источники ионов	да	необходима доработка	нет	ОИЯИ, ТРИНИТИ, ИТЭФ, ИСЭ
Импульсные нормально проводящие ускоряющие системы	да	да	необходима доработка	ИТЭФ, МИФИ, ИФВЭ, ОИЯИ, ИЯИ, ИЯФ
CW нормально проводящие ускоряющие системы	нет	нет	нет	- ИТЭФ, ИФВЭ, МИФИ, ИЯФ, ИЯИ,
СП ускоряющие системы	нет	нет	нет	- ИТЭФ, МИФИ, ИЯФ, ИЯИ ОИЯИ
«Теплые» магниты	да	да	нет	ИЯФ, ИФВЭ, ОИЯИ,
СП магниты	да	да	необходима доработка	ИЯФ, ОИЯИ
Современные системы ВЧ питания	необходима доработка	нет	нет	-, ИТЭФ, МИФИ, ОИЯИ, ИЯФ
Системы транспортировки пучка	да	да	необходима доработка	ИТЭФ, МИФИ, ИФВЭ, МРТИ, ИЯИ, ИЯФ
Диагностика и управление пучком	да	да	необходима доработка	ИТЭФ, ИЯИ, ИЯФ

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Диагностика и управление пучком	да	да	необходима доработка	ИТЭФ, ИЯИ, ИЯФ

Кадры ?

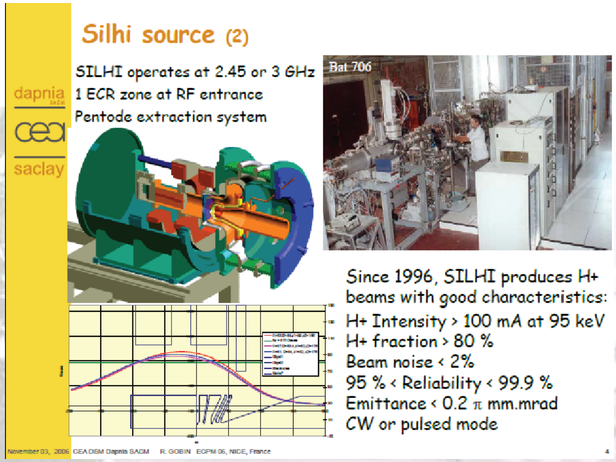
*Ion source list from SNS M.Stockli's report

56 different ion sources !

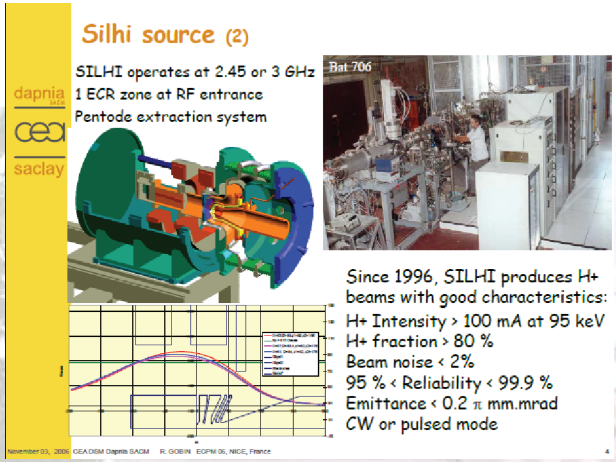
- *Electron Bombardment ion source*
- *Hollow Cathode ion source*
- *Reflex Discharge Multicusp source*
- *Cold- & Hot-Cathode PIG*
- *Electron Cyclotron Resonance ion source (ECR)*
- *Electron Beam Ion Source (EBIS)*
- *Surface Contact ion source*
- *Cryogenic Anode ion source*
- *Metal Vapor Vacuum Arc ion source (MEVVA)*
- *Sputtering-type negative ion source*
- *Plasma Surface Conversion negative ion source*
- *Electron Heated Vaporization ion source*
- *Hollow Cathode von Ardenne ion source*
- *Forrester Porus Plate ion source*
- *Multipole Confinement ion source*
- *EHD-driven Liquid ion source*
- *Microwave ion source*
- *XUV-driven ion source*
- *Arc Plasma ion source*
- *Surface Ionization ion source*
- *Charge Exchange ion source*
- *Capillary Arc ion source*
- *Von Ardenne ion source*
- *Capillaritron ion source*
- *Canal Ray ion source*
- *Pulsed Spark ion source*
- *Field Emission ion source*
- *Atomic Beam ion source*
- *Field Ionization ion source*
- *Arc Discharge ion source*
- *Multifilament ion source*
- *RF plasma ion source*
- *Freeman ion source*
- *Liquid Metal ion source*
- *Beam Plasma ion source*
- *Magnetron ion source*
- *CHORD*
- *Calutron ion source*
- *Bayard-Alpert type ion source*
- *Inverse Magnetron ion source*
- *FEBIAD ion source*
- *Nier ion source*
- *Bernas ion source*
- *Nielsen ion source*
- *Wilson ion source*
- *Recoil ion source*
- *Zinn ion source*
- *Plasmatron*
- *Duoplasmatron*
- *Duopigatron*
- *Laser ion source*
- *Penning ion source*
- *Monocusp ion source*
- *Bucket ion source*
- *Metal ion source*
- *Multicusp ion source*
- *Kaufman ion source*
- *Flashover ion source*

Ion Source

Ion Source


Silhi source (2)
dapnia
cea
saclay
SILHI operates at 2.45 or 3 GHz
1 ECR zone at RF entrance
Pentode extraction system
Bat 706
Since 1996, SILHI produces H+ beams with good characteristics:
H+ Intensity > 100 mA at 95 keV
H+ fraction > 80 %
Beam noise < 2%
95 % < Reliability < 99.9 %
Emittance < 0.2 π mm.mrad
CW or pulsed mode
November 03, 2006 CEA DSM Dapnia SACM R. GOBIN ECPM 06, NICE, France
4

Ion Source



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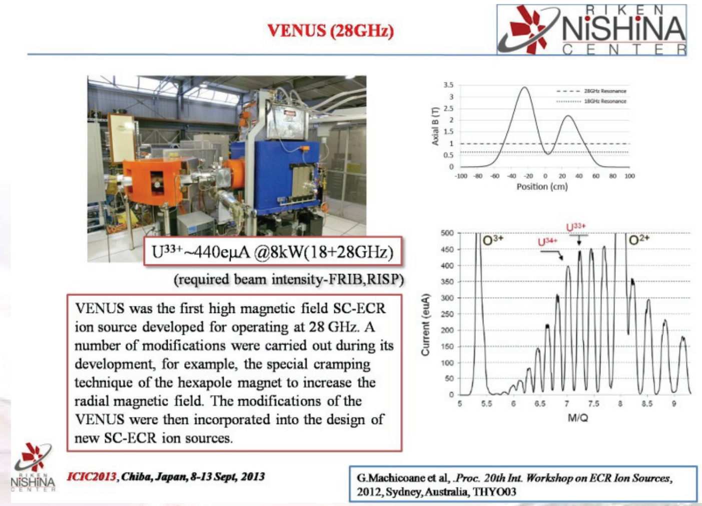
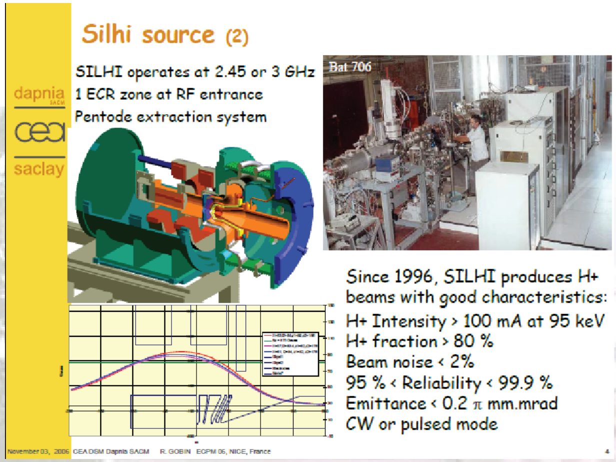


VENUS (28GHz)
RIKEN NISHINA CENTER
U33+~440eμA @8kW(18+28GHz)
(required beam intensity-FRIB,RISP)
VENUS was the first high magnetic field SC-ECR ion source developed for operating at 28 GHz. A number of modifications were carried out during its development, for example, the special cramping technique of the hexapole magnet to increase the radial magnetic field. The modifications of the VENUS were then incorporated into the design of new SC-ECR ion sources.
Axial B (T)
Position (cm)
Current (euA)
M/Q
O3+
U34+
U33+
O2+
ICIC2013, Chiba, Japan, 8-13 Sept, 2013
G.Machicoane et al, Proc. 20th Int. Workshop on ECR Ion Sources, 2012, Sydney, Australia, THYO03

Ion Source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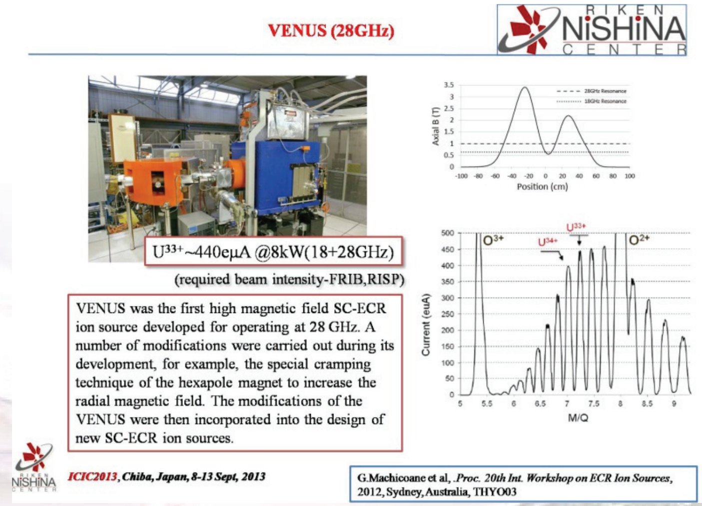
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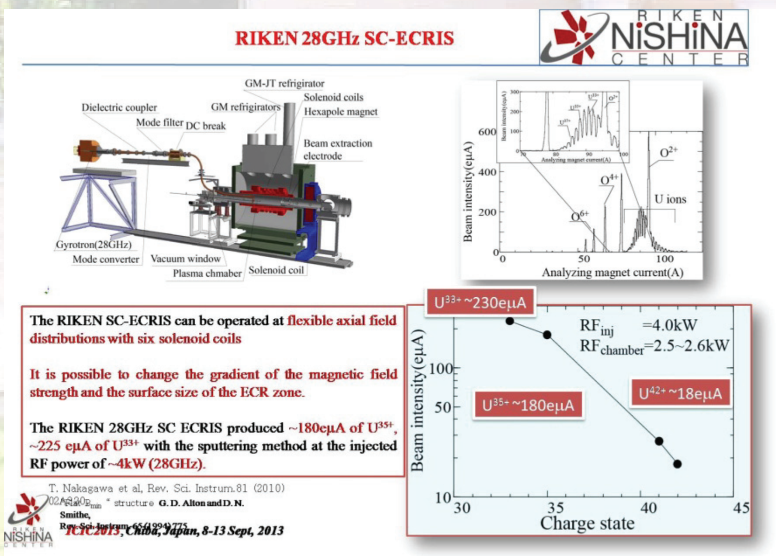
RIKEN 28GHz SC-ECRIS
RIKEN NiSHiNA CENTER
GM-JT refrigirator
Solenoid coils
Hexapole magnet
Dielectric coupler
GM refrigirators
Mode filter
DC break
Beam extraction electrode
Gyrotron(28GHz)
Mode converter
Vacuum window
Plasma chmaber
Solenoid coil
Beam intensity(eμA)
Analyzing magnet current(A)
O2+
O4+
O6+
U ions
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It is possible to change the gradient of the magnetic field strength and the surface size of the ECR zone.
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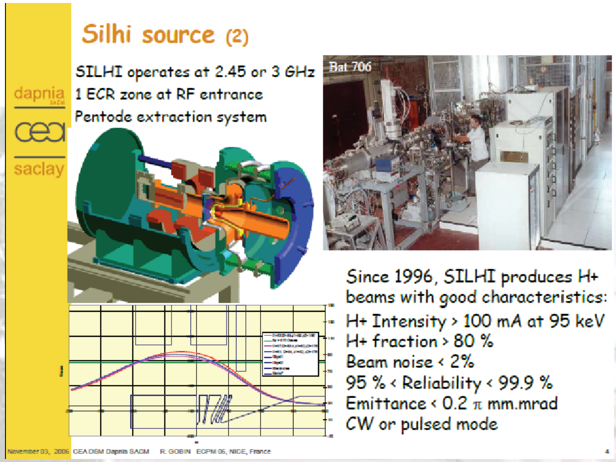
U33+~230eμA
U35+~180eμA
U42+~18eμA
RFinj =4.0kW
RFchamber=2.5~2.6kW
Beam intensity(eμA)
Charge state
T. Nakagawa et al, Rev. Sci. Instrum.81 (2010)
ICIC2013, Chiba, Japan, 8-13 Sept, 2013

Ion Source



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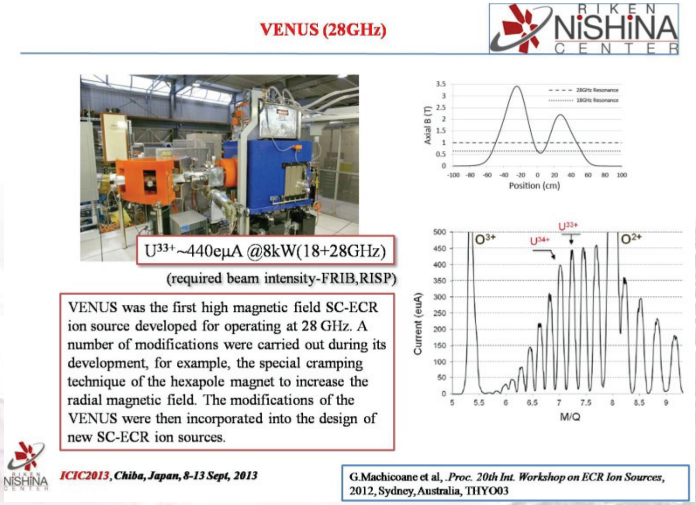

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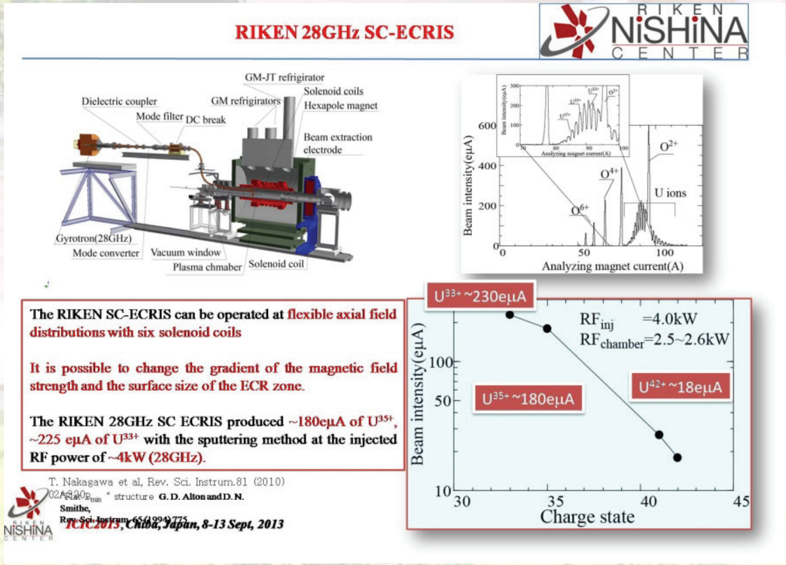

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Solenoid coils
Hexapole magnet
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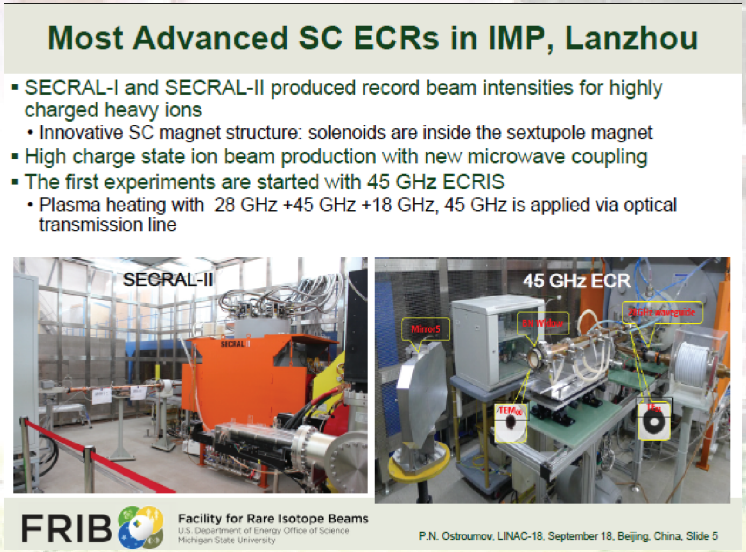
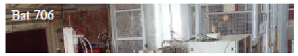


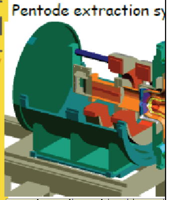
Most Advanced SC ECRs in IMP, Lanzhou
SECRAL-I and SECRAL-II produced record beam intensities for highly charged heavy ions
Innovative SC magnet structure: solenoids are inside the sextupole magnet
High charge state ion beam production with new microwave coupling
The first experiments are started with 45 GHz ECRIS
Plasma heating with 28 GHz +45 GHz +18 GHz, 45 GHz is applied via optical transmission line
SECRAL-II
45 GHz ECR
FRIB
Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University
P.N. Ostroumov, LINAC-18, September 18, Beijing, China, Slide 5

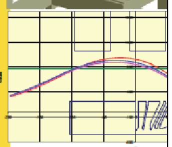
Ion Source

Silhi source (2)

SILHI operates at 2.45 or 3 GHz
1 ECR zone at RF entrance
Pentode extraction sy





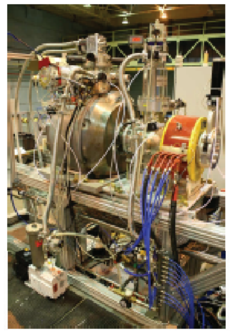


dapnia
cea
saclay

November 03, 2006 CEA DSM Dapnia SACM R. GOBIN ECPM 06

U-400M DECRIS-SC2

(Hybrid type ion source – superconducting solenoids, permanent magnet hexapole)



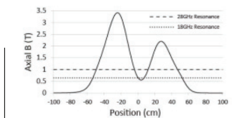
MAIN PARAMETERS	
Operating frequency	14 ÷ 18 GHz
UHF power range	50 ÷ 1000 W
Axial magnetic field (injection/extraction)	1.9 / 1.4 T
Coils power consumption	10 kW (cryocooler)
Coil current	< 100 A
Radial magnetic field	1.0 T
Plasma chamber diameter	74 mm
Source diameter / length	690 / 570 mm
Source weight	~ 700 kg

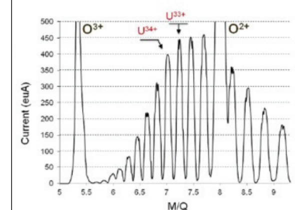
* - 18 GHz

Полученные пучки ионов из DECRIS-SC2 (14 GHz)														
A/Z	3.2	2.66	2.28	3.55	2.91	5	4.44	3.63	3.33	3.73	5.6	4.94	4.4	5.65
Ion	O^{5+}	O^{6+}	O^{7+}	S^{9+}	S^{11+}	Ar^{8+}	Ar^{9+}	Ar^{11+}	Ar^{12+}	Fe^{15+}	Kr^{15+}	Kr^{17+}	Xe^{30+}	Bi^{37+}
I, (eμA)	920	820	50	265	90	880	680	250	120	20*	250	150	~ 1	~ 4*
I, (pμA)	184	130	7	30	8	110	75	23	10	1.3	16	9	0.03	0.1

VENUS (28GHz)

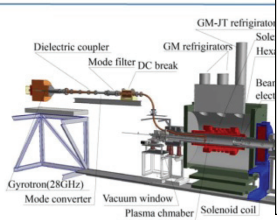
RIKEN NISHINA CENTER





...ne et al, *Proc. 20th Int. Workshop on ECR Ion Sources*, ...y, Australia, THYO03

RIKEN 28



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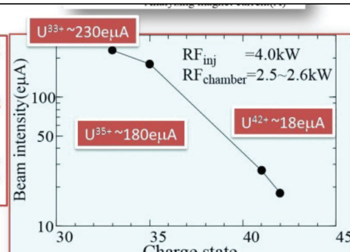
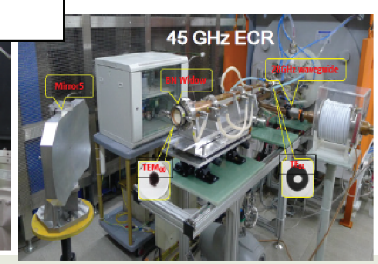


T. Nakagawa et al, Rev. Sci. Instrum.81 (2010) 02A320
G. D. Alton and D. N. Smithe, Rev. Sci. Instrum. 65 (1994) 775
ICIS2013, Chiba, Japan, 8-13 Sept, 2013

...s in IMP, Lanzhou

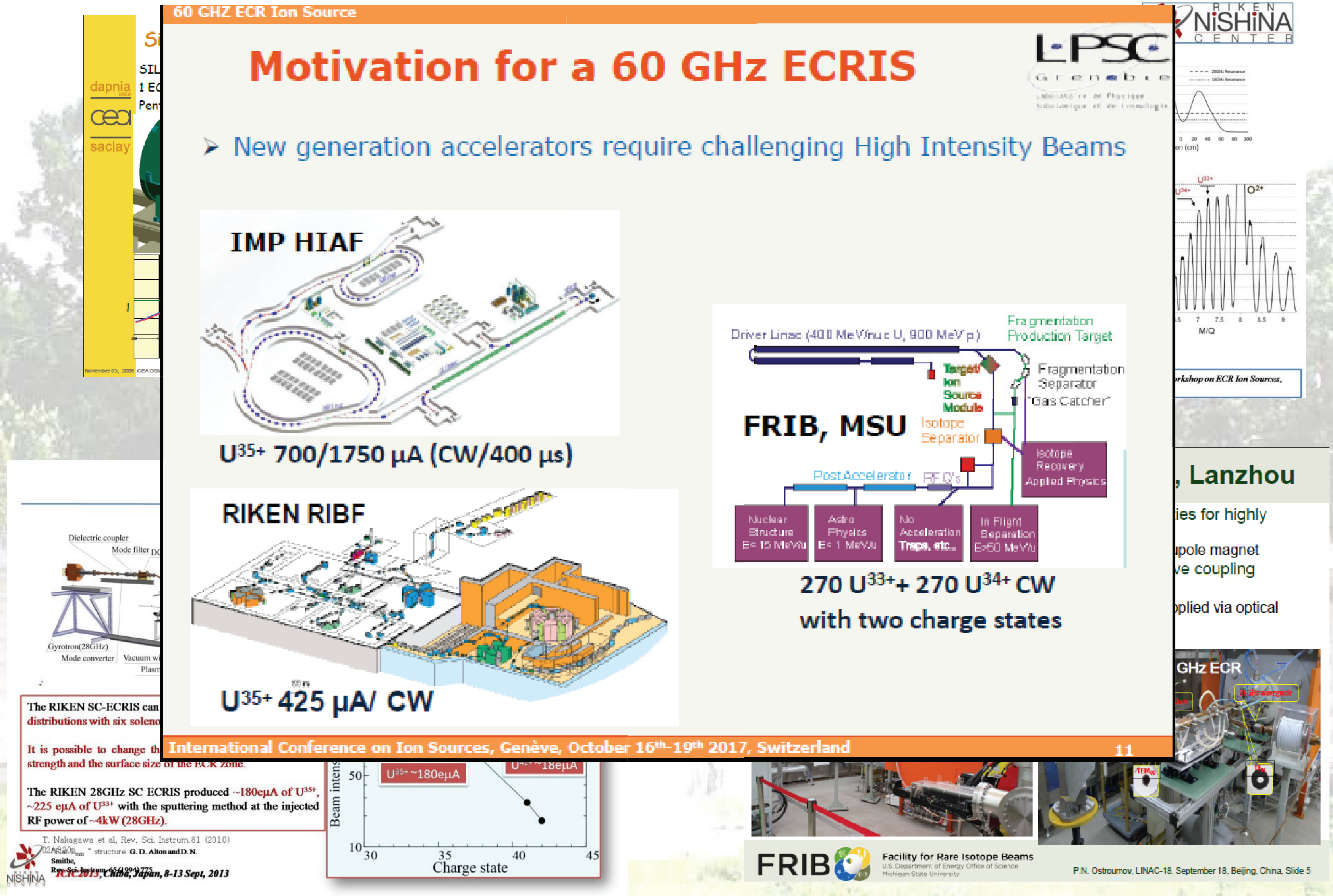
...beam intensities for highly
...inside the sextupole magnet
...new microwave coupling
...Hz ECRIS
...z, 45 GHz is applied via optical



FRIB Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

P.N. Ostroumov, LINAC-18, September 18, Beijing, China, Slide 5

Ion Source


60 GHZ ECR Ion Source
Motivation for a 60 GHz ECRIS
LPSC Grenoble
New generation accelerators require challenging High Intensity Beams
IMP HIAF
U35+ 700/1750 µA (CW/400 µs)
RIKEN RIBF
U35+ 425 µA/ CW
FRIB, MSU
Driver Linac (400 MeV/u for U, 900 MeV p)
Fragmentation Production Target
Target/ Ion Source Module
Fragmentation Separator
"Gas Catcher"
Isotope Separator
Isotope Recovery Applied Physics
Post Accelerator
RFQ's
Nuclear Structure E≤ 15 MeV/u
Astro Physics E≤ 1 MeV/u
No Acceleration Traps, etc.
In Flight Separation E>50 MeV/u
270 U33+ + 270 U34+ CW
with two charge states
International Conference on Ion Sources, Genève, October 16th-19th 2017, Switzerland
11
RIKEN NISHINA CENTER
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, Lanzhou
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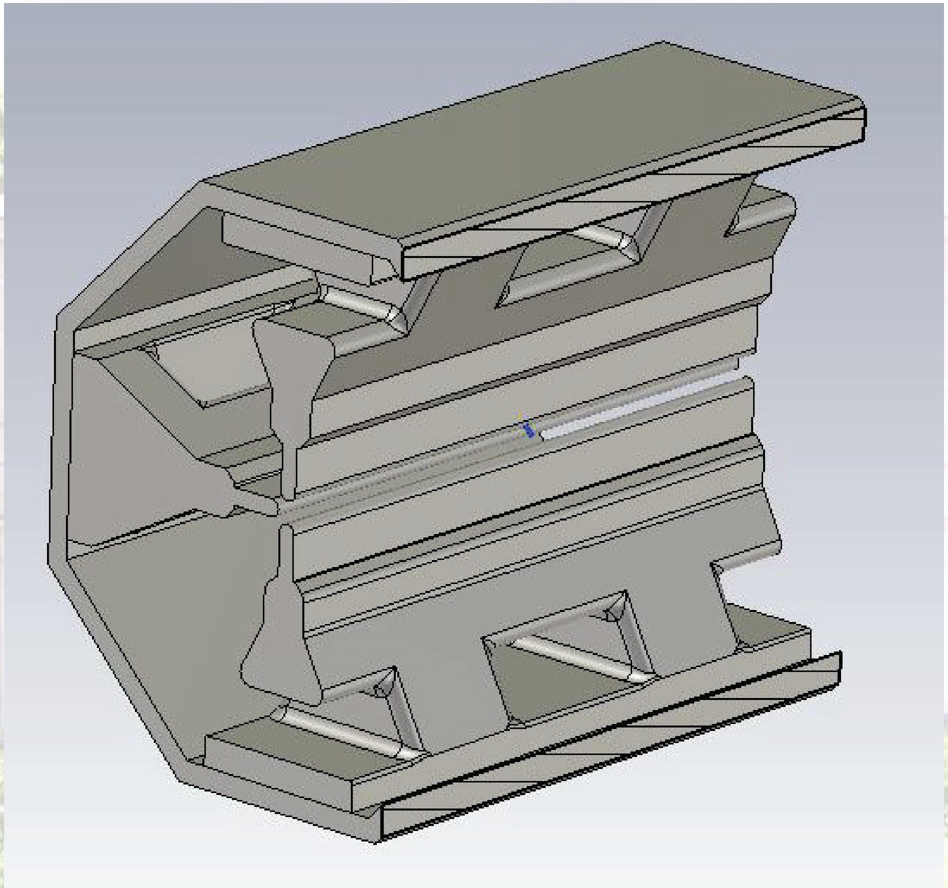
Michigan State University
P.N. Ostroumov, LINAC-18, September 18, Beijing, China, Slide 5

RFQ
shifted coupling windows

V.A. Andreev, G. Parisi, *in Proc. PAC'93,* p. 3124.



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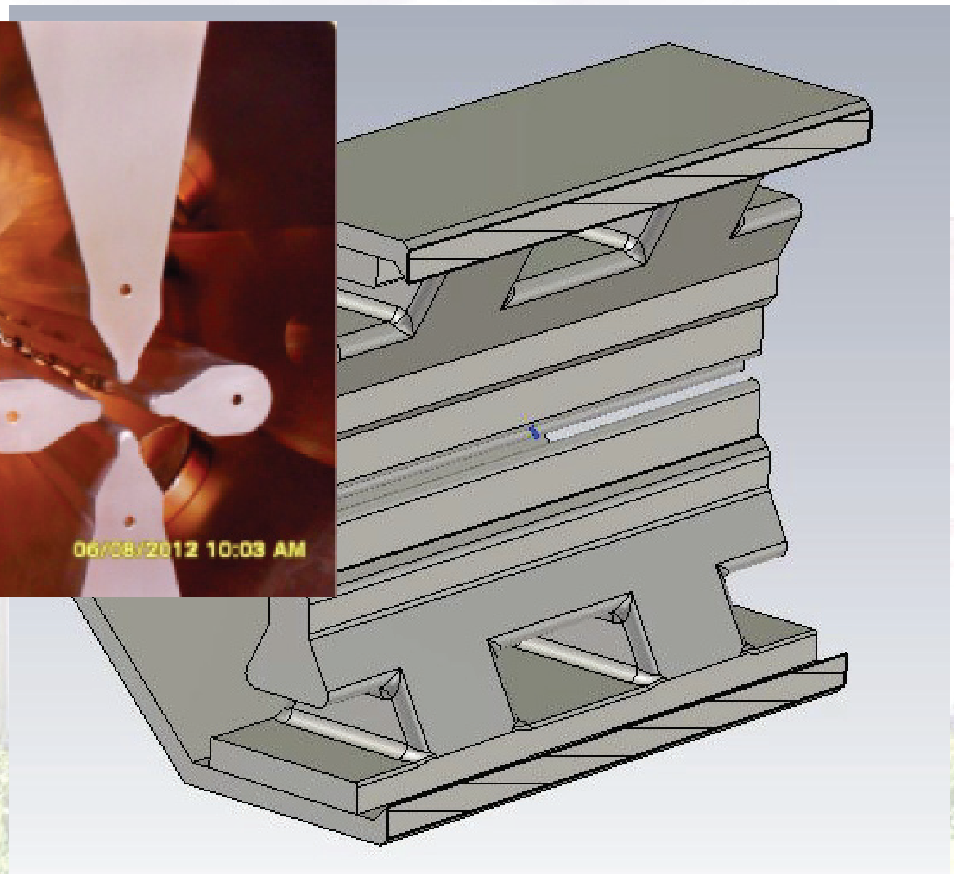
ATLAS RFQ
Photo- P.Ostroumov
HIAT2012



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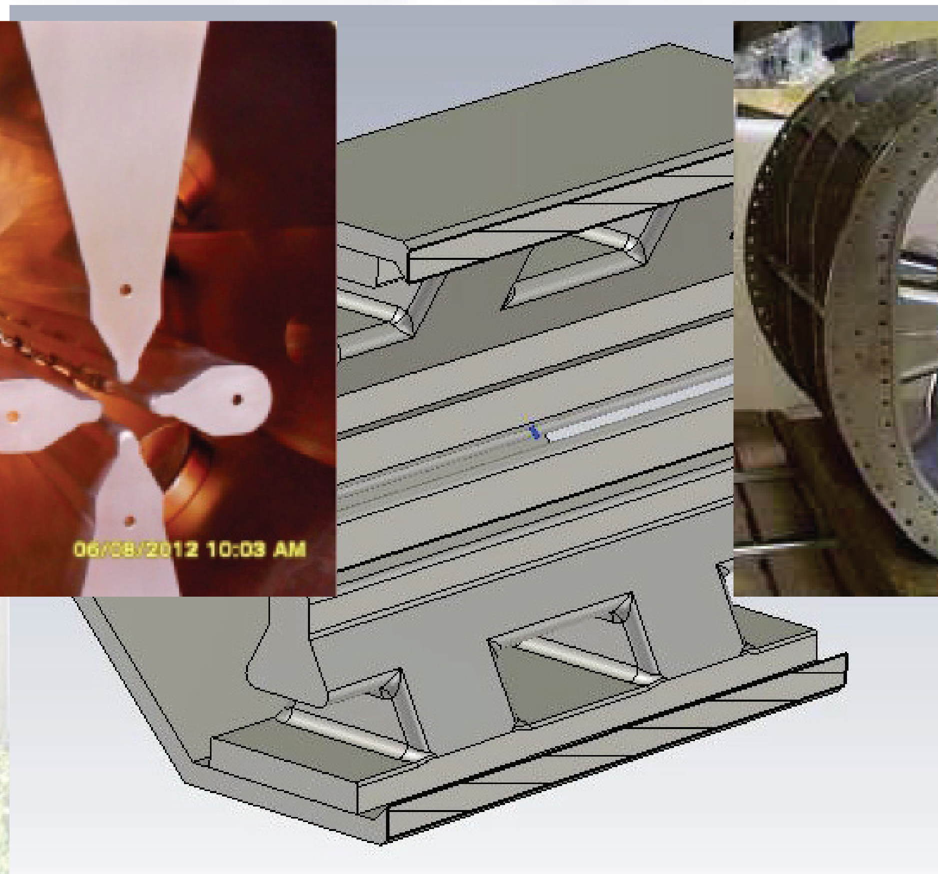

LNL-INFN SC RFQ
Photo – G.Bisoffi
http://accelconf.web.cern.ch/accelconf/e02/TALKS/WEBLA001.pdf

RFQ
shifted coupling windows

V.A. Andreev, G. Parisi, *in Proc. PAC'93,* p. 3124.

ATLAS RFQ
Photo- P.Ostroumov
HIAT2012

LNL-INFN SC RFQ
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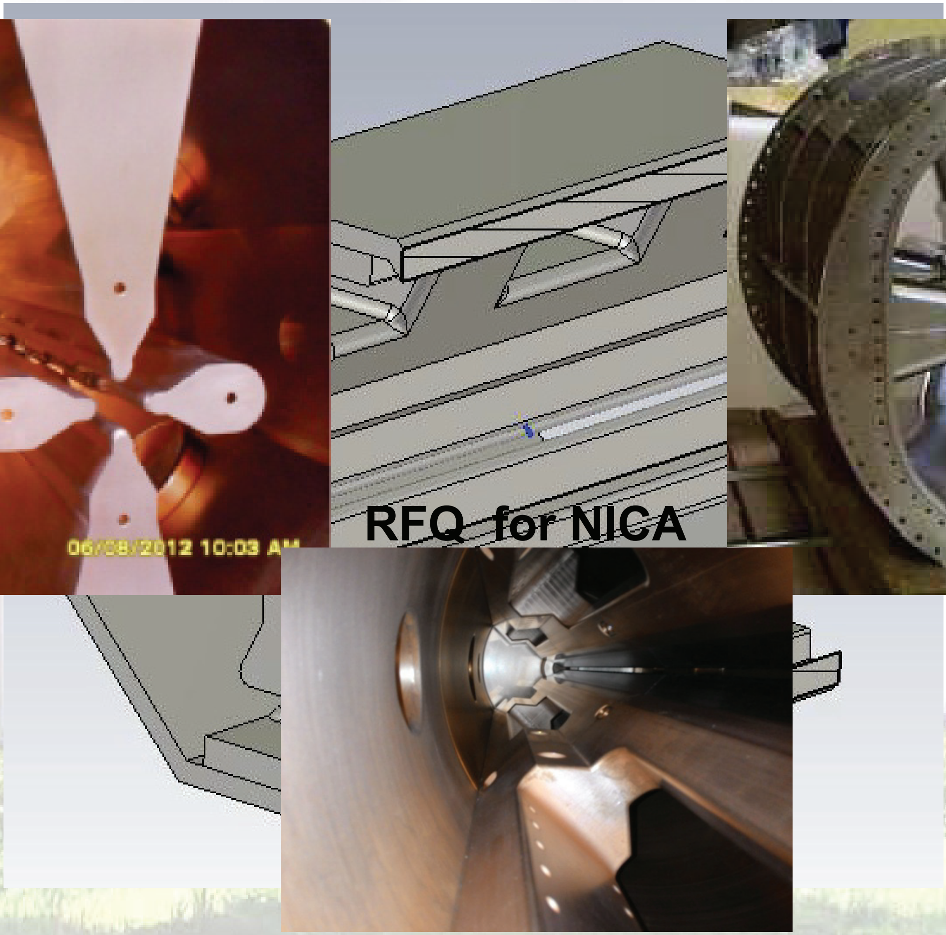
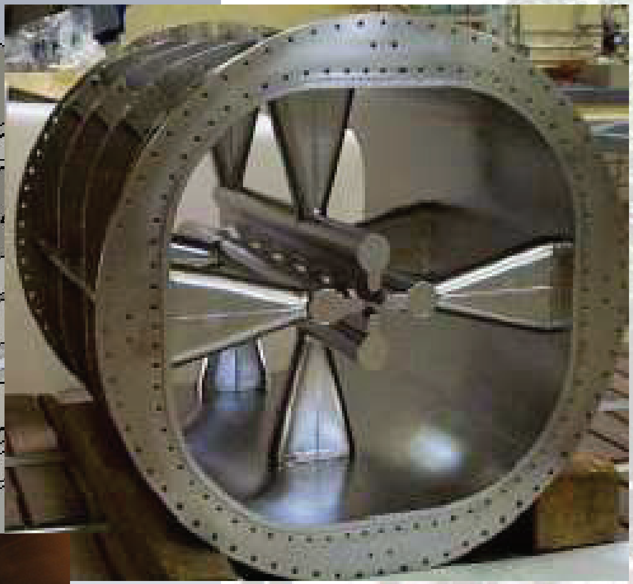


RFQ for NICA



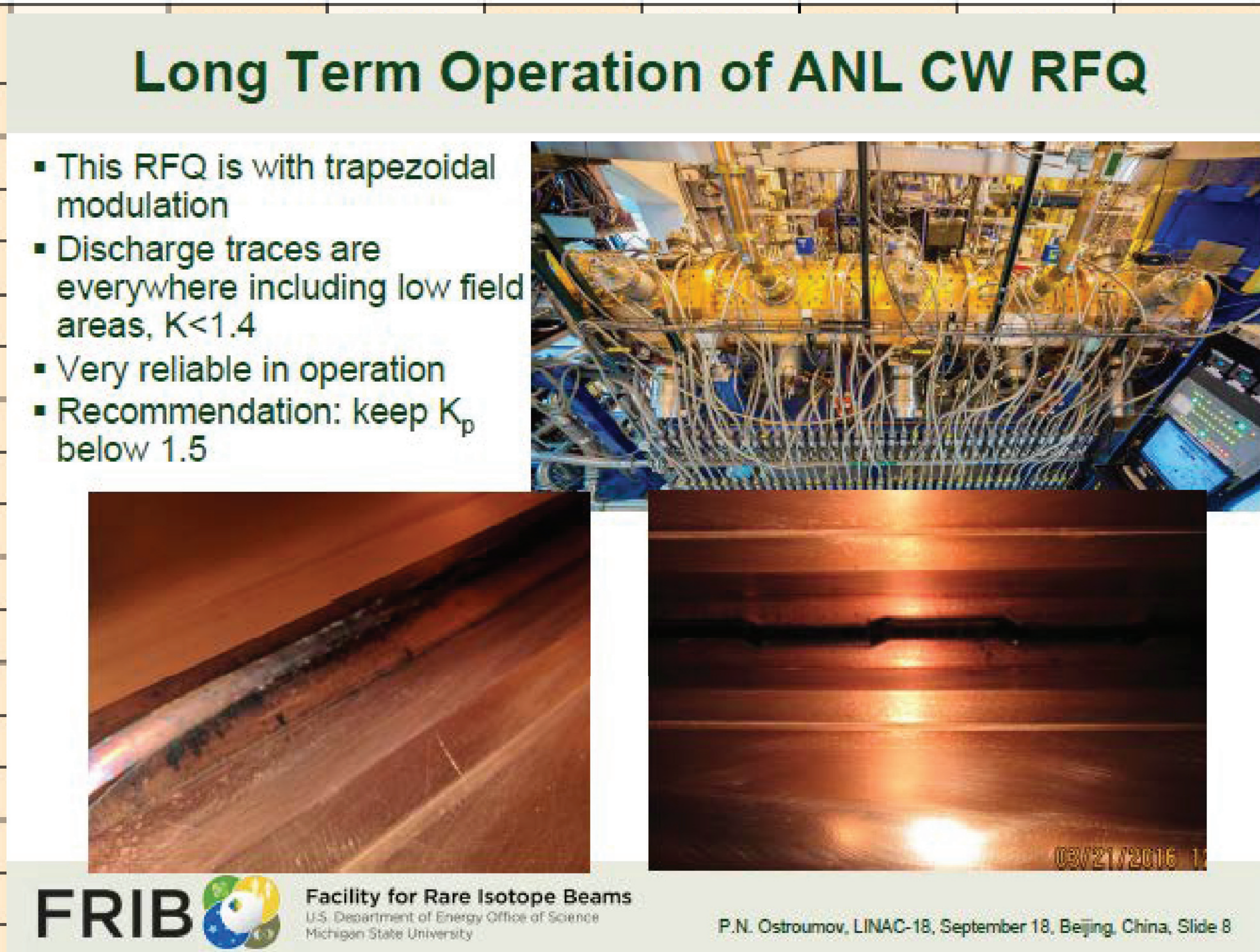
Progress in RFQ family (incomplete)

Project	Lab	Ion	Frequency (MHz)	Voltage (kV)	Vane length (m)	Current (emA)	Duty factor (%)	Inj. E (keV)	Exit E (MeV)	Type	State
SNS	ORNL	H-	402.5	83	3.72	38	6.2	65	2.5	4-vane	Upgrade
J-PARC	JAEA/KEK	H-	324	82.9/82.9/81.0	3.11/3.17/3.62	50	3	50	3	4-vane	Upgrade
LINAC4	CERN	H-	352.2	78	3.06	80	7.5	45	3	4-vane	Operation
CPHS	THU	P	325	60-132	3	50	2.5	50	3	4-vane	Operation
CSNS	IHEP	P	324	80	3.62	40	1.24	50	3	4-vane	Operation
IPHI	CEA	P	352.2	80-120	6	100	CW		3	4-vane	Commission
C-ADS inj-I	IHEP	P	325	55	4.69	10	CW	35	3.2	4-vane	Upgrade
C-ADS inj-II	IMP	P	162.5	65	4.21	10	CW	35	2.1	4-vane	Operation
PXIE(PIP II)	FNAL	P	162.5	60	4.21	5	CW	35	2.1	4-vane	Commission
FRANZ	IAP	P	175	75	1.75	200	CW	120	0.7	4-rod	Commission
SARAF	SNRC	D	176	65	3.8	5	CW	20	3	4-rod	Upgrade
IFMIF	*INFN*	*D*	*175*	*79-132*	*9.8*	*130*	*CW*	*50*	*5*	*4-vane*	*Assembly*
CIMF	*IMP*	*D*	*162.5*	*65*	*5.27*	*10*	*CW*	*20*	*3*	*4-vane*	*Construction*
SSC-Linac	IMP	A/q=7	53.667	70	2.51	0.5	CW	25	1	4-rod	Operation
Spiral2	GANIL	A/q=3	88	100-113	5	5	CW	60	2.25	4-vane	Commission
FRIB	*MSU*	*A/q=7*	*80.5*	*60-112*	*5.04*	*0.45*	*CW*	*84*	*3.5*	*4-vane*	*Assembly*
LEAF(HIAF)	*IMP*	*A/q=7*	*81.25*	*70*	*5.98*	*2*	*CW*	*98*	*3.5*	*4-vane*	*Construction*

- The high intensity RFQs include proton, deuteron and high ions machines.
- Most efforts and problems are on the CW high power RF and high power beam.

Progress in RFQ family (incomplete)

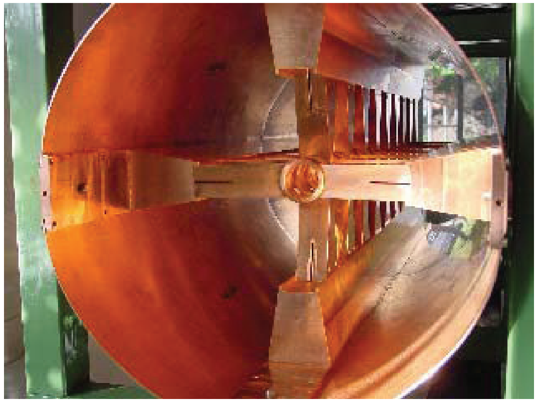
Project	Lab	Type	State
SNS	ORNL	4-vane	Upgrade
J-PARC	JAEA/KEK	4-vane	Upgrade
LINAC4	CERN	4-vane	Operation
CPHS	THU	4-vane	Operation
CSNS	IHEP	4-vane	Operation
IPHI	CEA	4-vane	Commission
C-ADS inj-I	IHEP	4-vane	Upgrade
C-ADS inj-II	IMP	4-vane	Operation
PXIE(PIP II)	FNAL	4-vane	Commission
FRANZ	IAP	4-rod	Commission
SARAF	SNRC	4-rod	Upgrade
IFMIF	*INFN*	*4-vane*	*Assembly*
CIMF	*IMP*	*4-vane*	*Construction*
SSC-Linac	IMP	4-rod	Operation
Spiral2	GANIL	4-vane	Commission
FRIB	*MSU*	*4-vane*	*Assembly*
LEAF(HIAF)	*IMP*	*4-vane*	*Construction*



- The high intensity RFQs include proton, deuteron and high ions machines.
- Most efforts and problems are on the CW high power RF and high power beam.

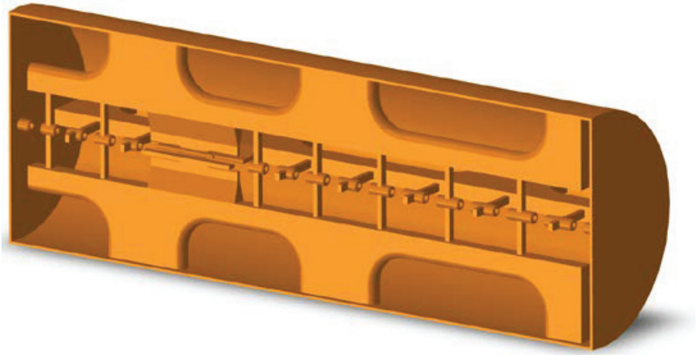
Секции на Н-резонаторах на промежуточные энергии

ППКФ, ИФВЭ,
В.А. Тепляков

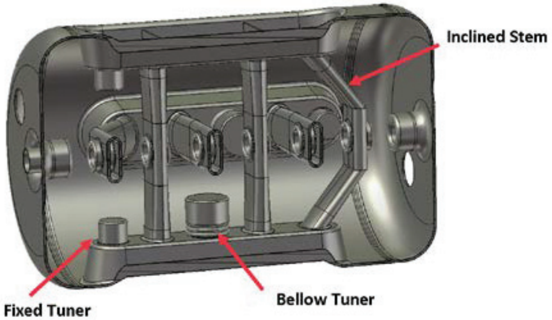


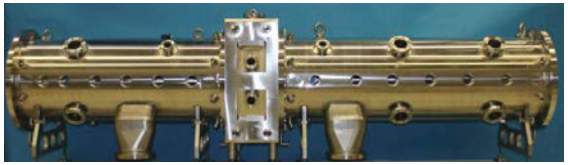
СН резонаторы,
IAP FU

CH-DTL,
IAP FU и GSI

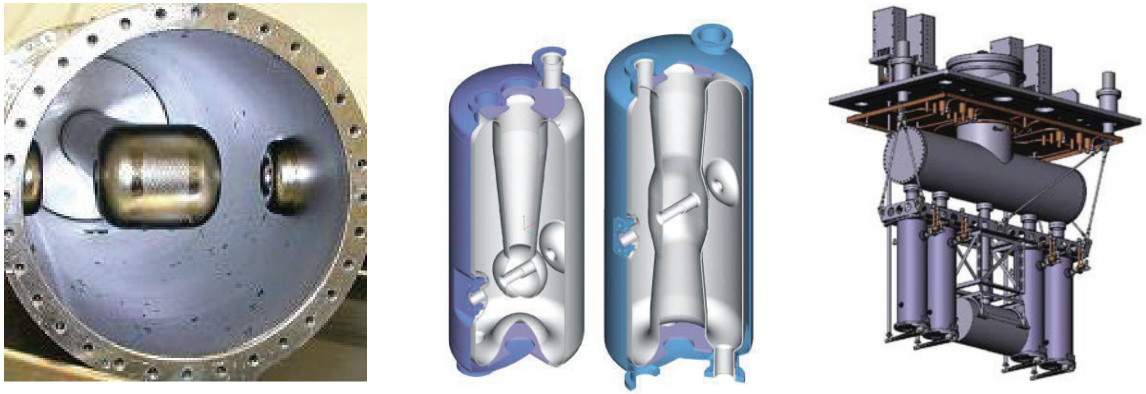


Гибридный ПОКФ,
ИТЭФ, МИФИ, ANL

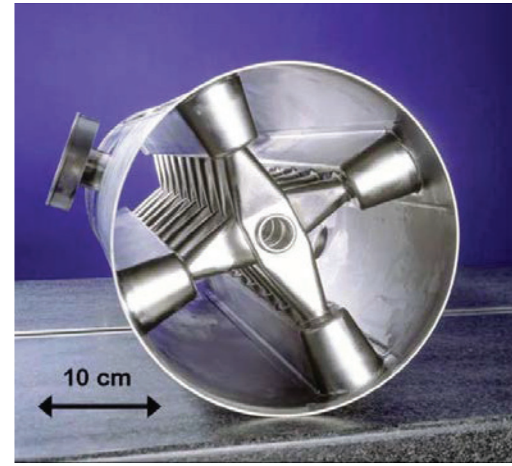




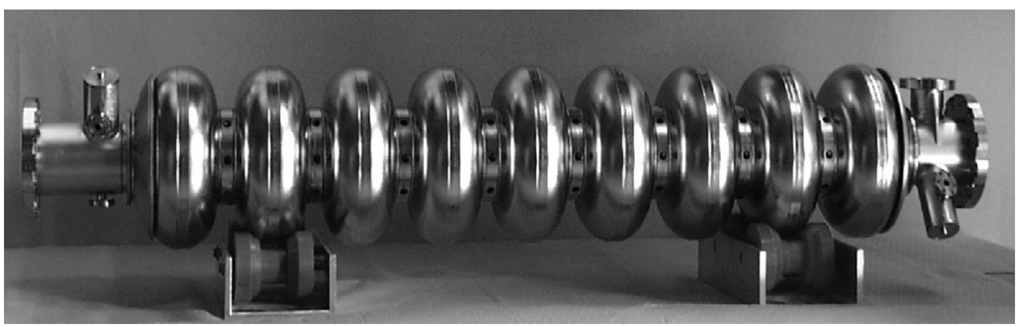
➢SC cavities: types and typical energy gains



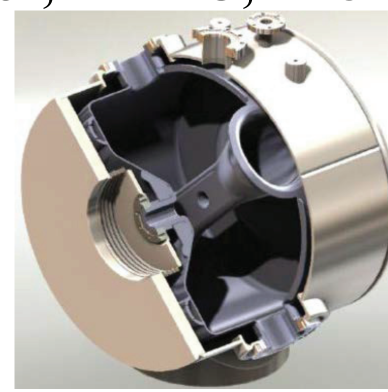
QWR and HWR β=0.01-0.17, 6-7 MV/m (LNF INFN+E.Zanon, TRIUMF+PAVAC, …, bulk Nb), 5-6 MV/m (LNF INFN, Nb/Cu)



CH, β=0.1, 5-7 MV/m (GSI, IAP FU, RI 325 and



Elliptical cavities, β=0.2-1.0, up to 35 MV/m (1300 MHz, KEK, DESY, FNAL ...), 15-16 MV/m (704 MHz, ESS), 30-40 MV/m (800 MHz, LANL)



Spoke-cavity, β=0.1-0.25,
8 MV/m (ANL, 324 MHz)
12-16 MV/m (FNAL, 324 MHz),
15-18 MV/m (ESS, 325 MHz),
8 MV/m (JFZ, 700 MHz)

Commissioning procedures of CW proton linac

- **Hardware calibration – To verify the parameters of the key hardwares**
  - RFQ Voltage was calibrated with beam energy spread; BPM offset calibration, cavity phase setting, phase scanning ...

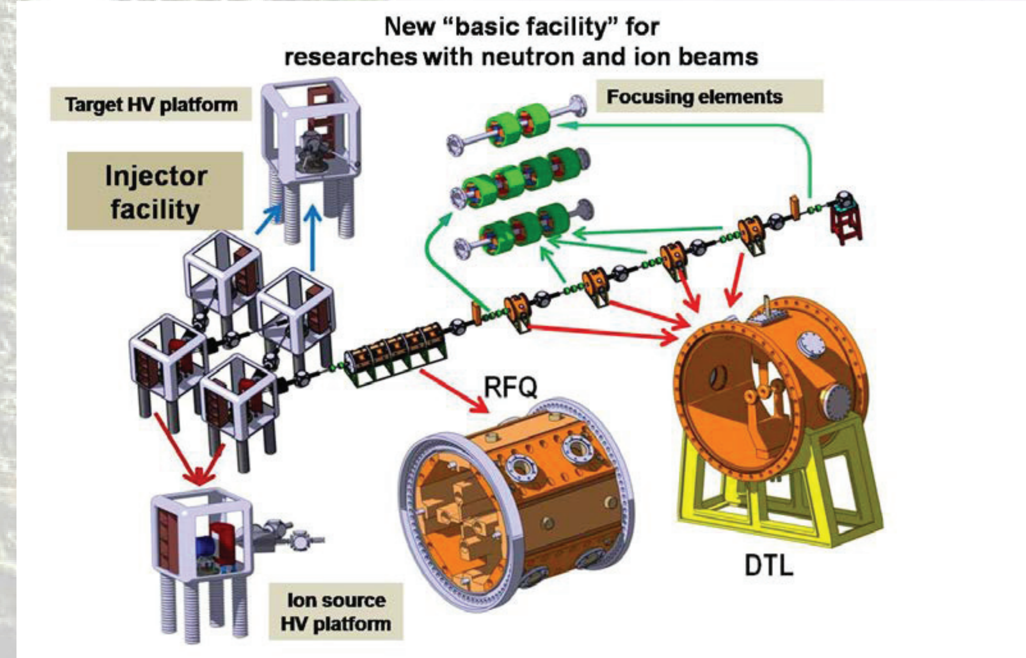
- **Beam distribution reconstruction - To match the beam between different section**
  - Lattice initial setting, pulse beam commissioning; Beam emittance and twiss parameters measurements; Trace back to simulate and get new lattice; Initial beam parameters rebuilt and Lattice re-setting; Match tuning for high power,....

- **Beam tuning with CW high power – To ramp the beam power for the whole linac**
  - Always start from pulse beam commissioning, increase pulse-length little bit, and switch to CW with lower intensity.
  - Double-check MPS, ramping mode, beam loss detection system.

Normal conducting linacs

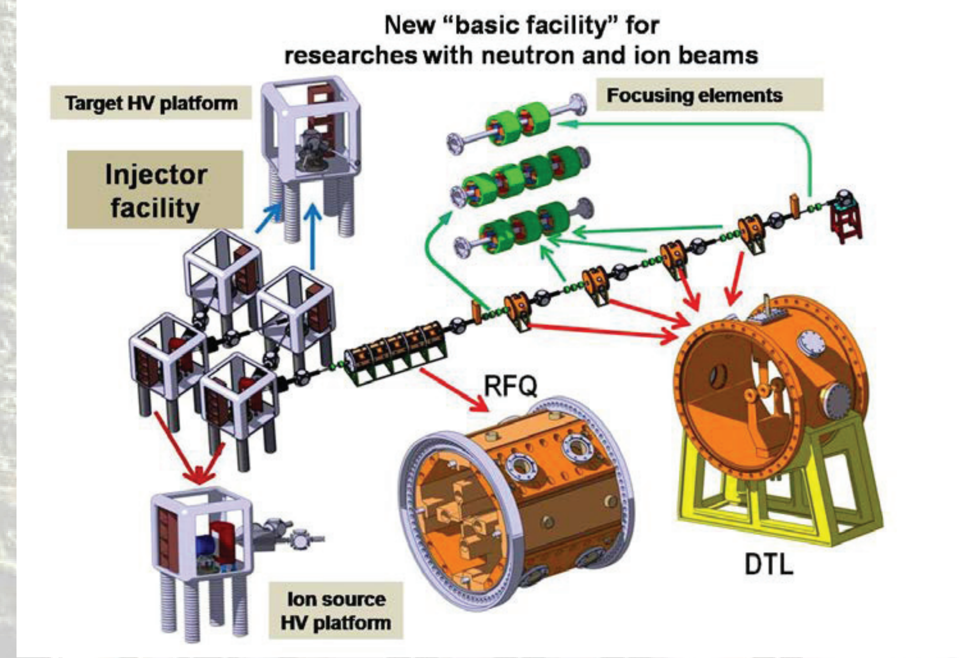
Normal conducting linacs

BELA

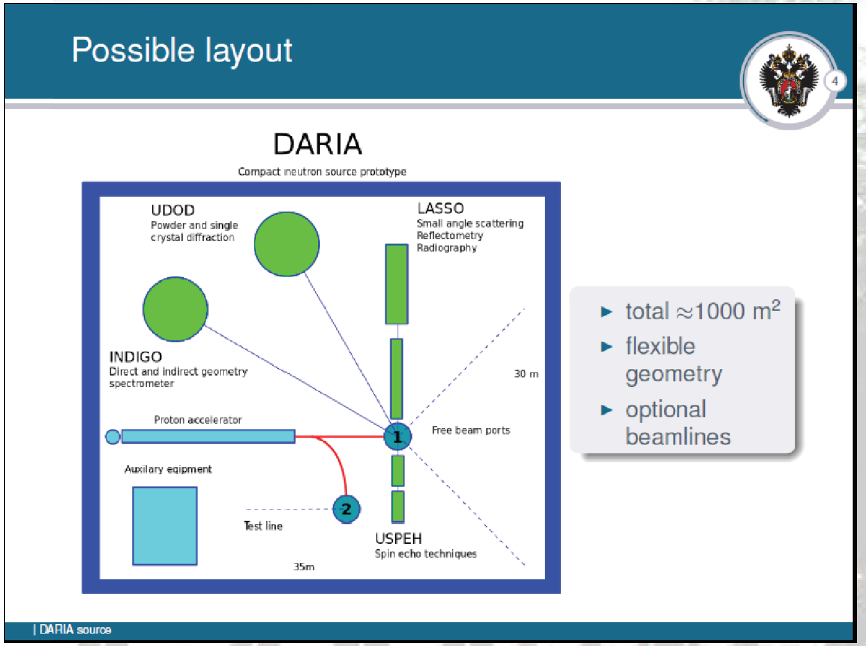


Normal conducting linacs

BELA



DARIA

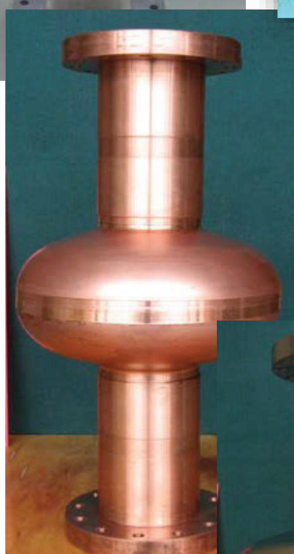


➤Joint Dubna-Moscow-Minsk SRF activities









Special thanks to:

Sergey Polozov, Gennadiy Kropachev, Alexey Sitnikov,

Michail Lalayan, Boris Sharkov, Igor Meshkov,

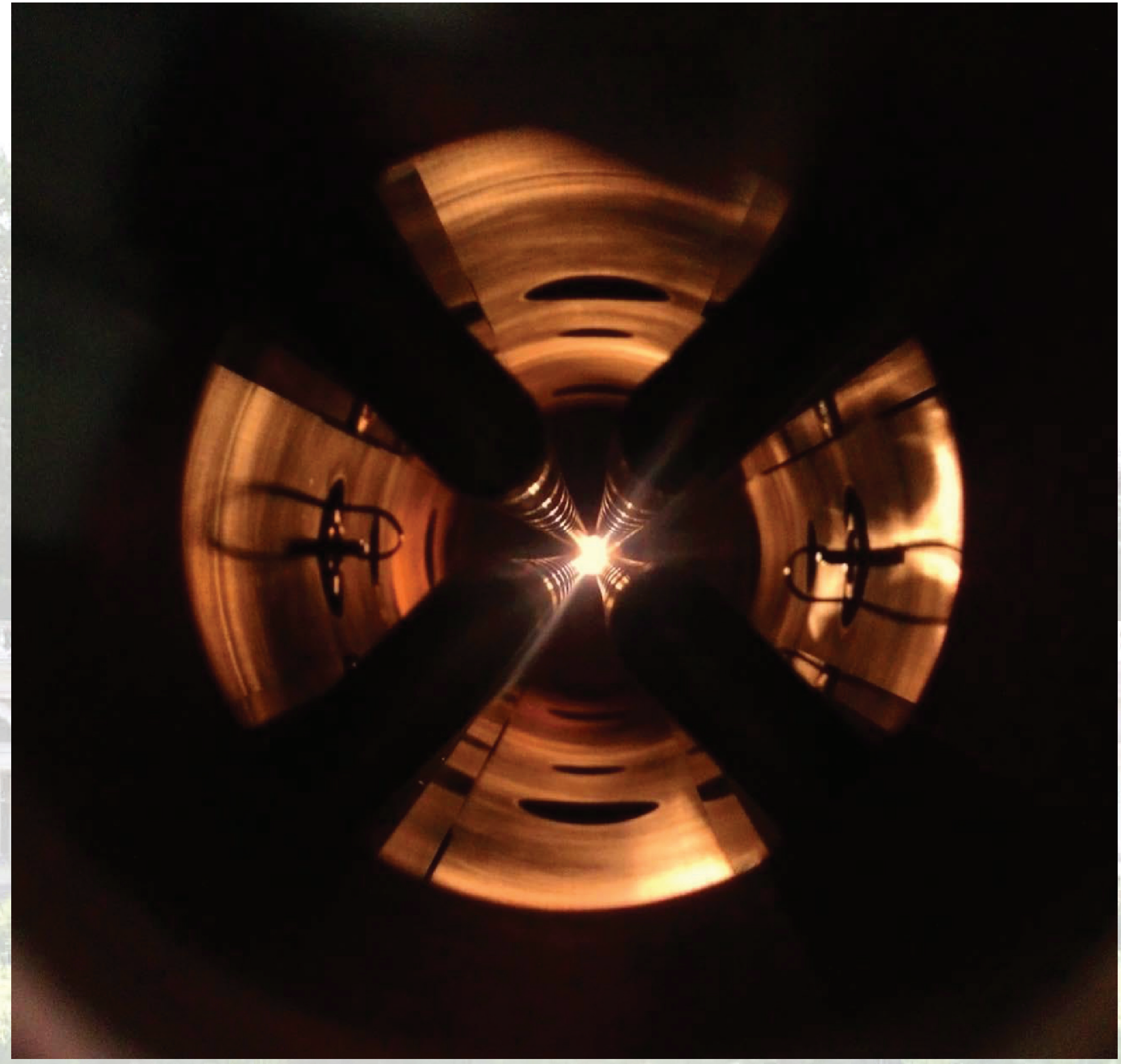
Viktor Aksenov, Leonid Grigorenko, Andrey Fomichev,

Andrey Butenko, Evgeniy Syresin,

Leonid Kravchuk, Alexandr Feshenko,

Valentin Paramonov, Peter Ostroumov,

Per aspera ad astra

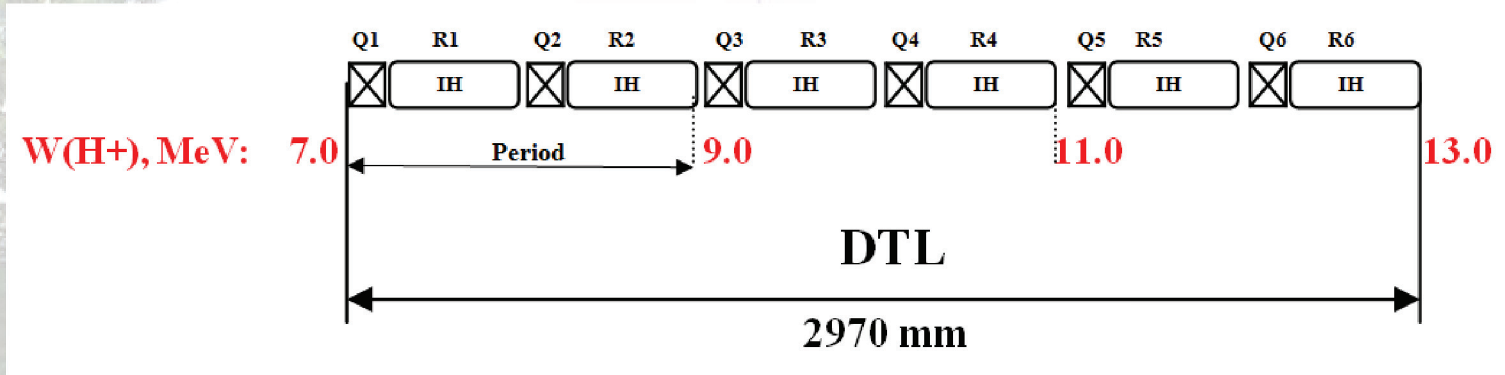


Per aspera ad astra

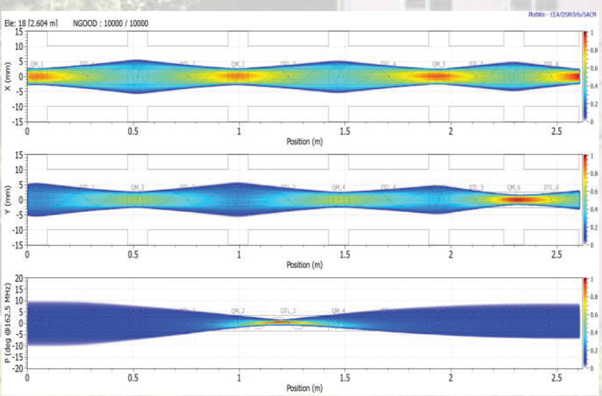
Thank You for attention!

Join us!

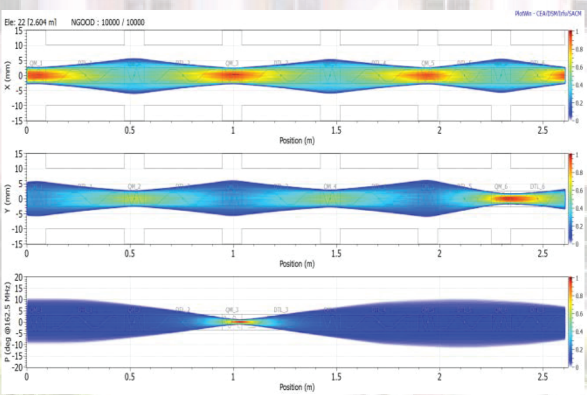
Nuclotron-based Ion Collider fAcility (NICA)



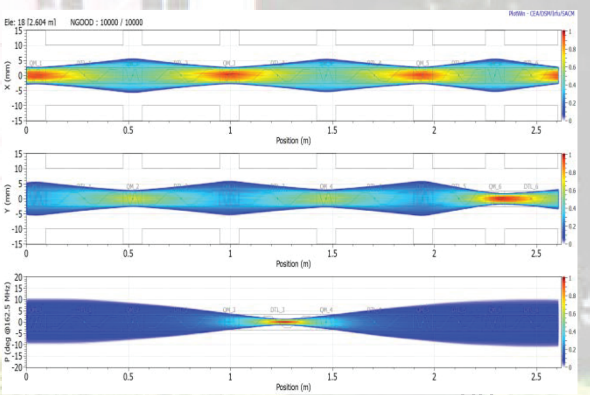
Z/A=1 W=7 - 13 MeV



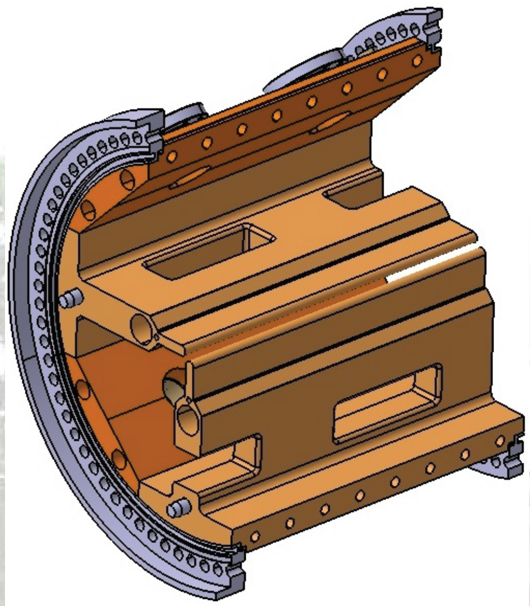
Z/A=2 W=14 - 14 MeV



Z/A=3 W=21 - 21 MeV

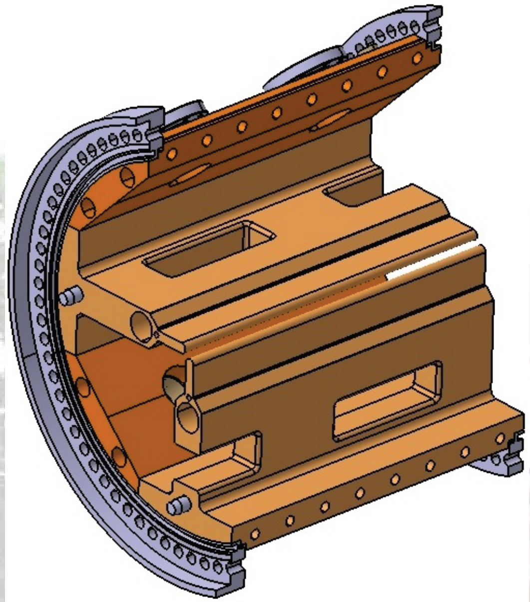


RFQ



Ions	H^+
Operating frequency	162.5 MHz
Beam energy	0.060÷1.5 MeV
Injection current	10 mA
Normalized emittance	1 π mm mrad
Normalized acceptance	10 π mm mrad
Synchronous phase	-90÷-35 deg
Intervane voltage	155 kV
Maximum field strength	1.6 Kp
Average radius	9 mm
Vane radius of curvature	7.2 mm
Maximum vane modulation	1.8
RF power losses	225 kW
Length	2.7 m

RFQ



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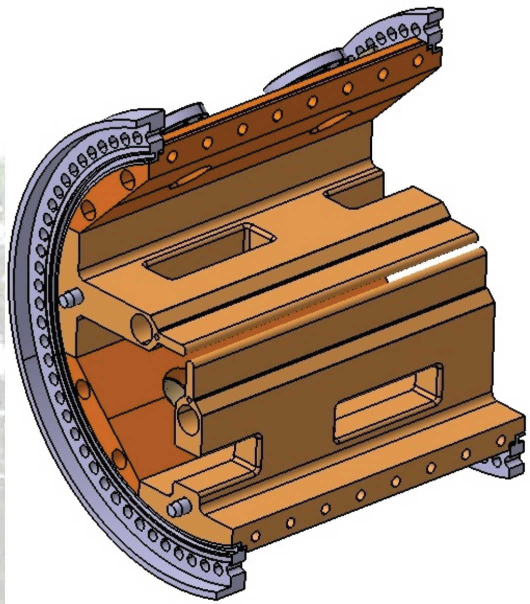
+Buncher in front of it

RFQ



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+Buncher in front of it

http://accelconf.web.cern.ch/AccelConf/e94/PDF/EPAC1994_1180.PDF

6D-High Current Beam Matching at RFQ Entrance

A.I. Balabin and G.N. Kropachev
ITEP, 25, Bolshaja Cherjomushkinskaja, Moscow 117259, Russia

Abstract

Envelope equations for the bunched beam with electrostatic interaction of bunches represented as uniformly charged ellipsoids are derived. On the base of the equations solution injection conditions for a matched beam are formulated at the RFQ entrance which fulfilment necessitates beam modulation in the longitudinal velocities. Introduction of the initial sinusoidal velocity modulation at the linac operating frequency is shown by the macroparticle method to permit considerable reduction of high current beam emittance growth in RFQ.

1 INTRODUCTION

by the quadratic form

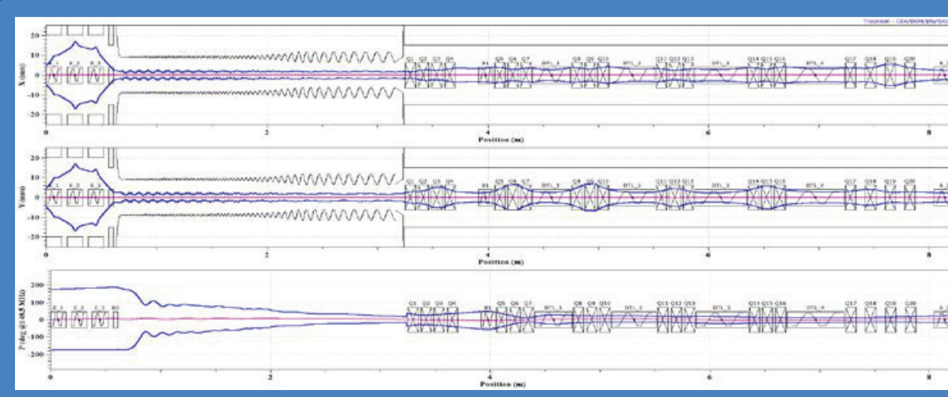
$$U(x,y,\zeta) = -\frac{\rho}{2\varepsilon_0}[M_x^* x^2 + M_y^* y^2 + M_z^* \zeta^2]. \quad (1)$$

Here ρ is the space-charge density; ε_0 is the electric constant; x, y, ζ are the coordinates originated from the given bunch centre; $M_{x,y,z}^*$ are the ellipsoid form factors with mutual influence of the bunches.

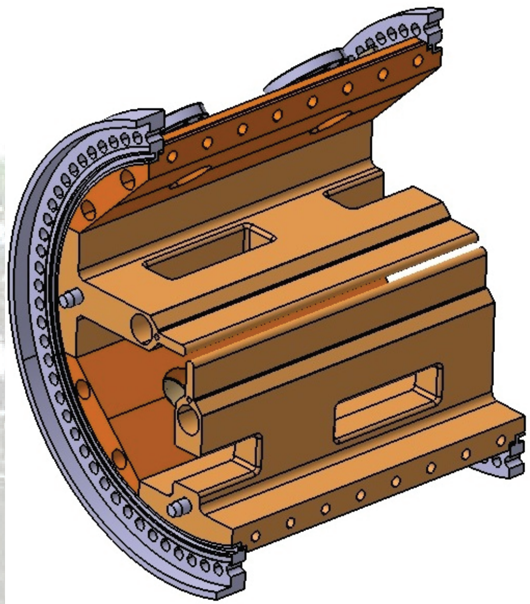
Factors $M_{x,y,z}^*$ may be represented in the form

$$M_{x,y,z}^* = M_{x,y,z} + \Delta M_{x,y,z} \quad (2)$$

where $M_{x,y,z}$ are the single ellipsoid form factors [2, 3]; $\Delta M_{x,y,z}$ are the corrections to the form factors caused by electrostatic bunch interaction.



RFQ



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+Buncher in front of it

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1 INTRODUCTION

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$U(x, y, \zeta)$

Here ρ is the spa... stant; x, y, ζ are t... bunch centre; $M_{x,y,z}$ ... mutual influence of the bunches.

Factors $M^*_{x,y,z}$ may be represented in the form

$$M^*_{x,y,z} = M_{x,y,z} + \Delta M_{x,y,z} \quad (2)$$

where $M_{x,y,z}$ are the single ellipsoid form factors [2, 3]; $\Delta M_{x,y,z}$ are the corrections to the form factors caused by electrostatic bunch interaction.

Transmission up to 98%
Decrease of emittance growth more than 2 times

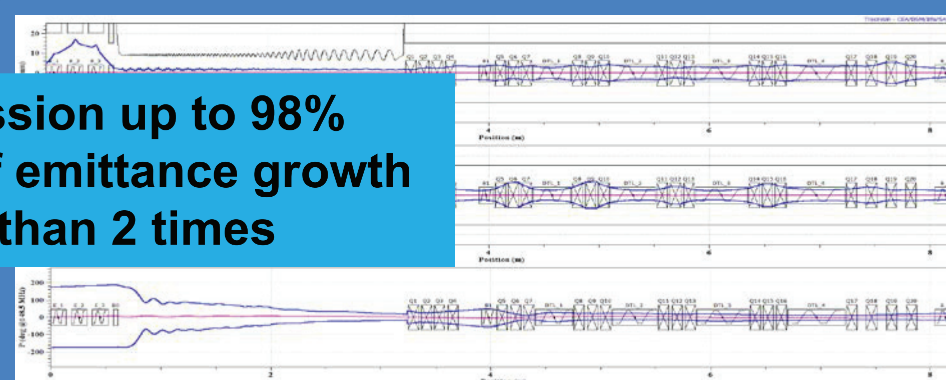
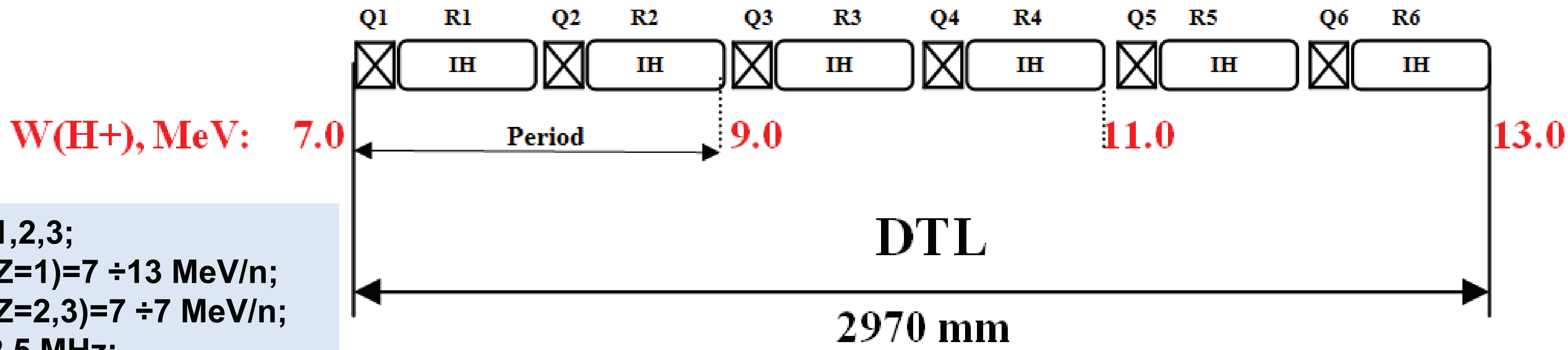
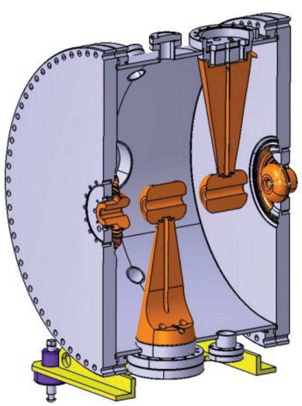


Схема канала DTL для нового инжектора проекта NICA

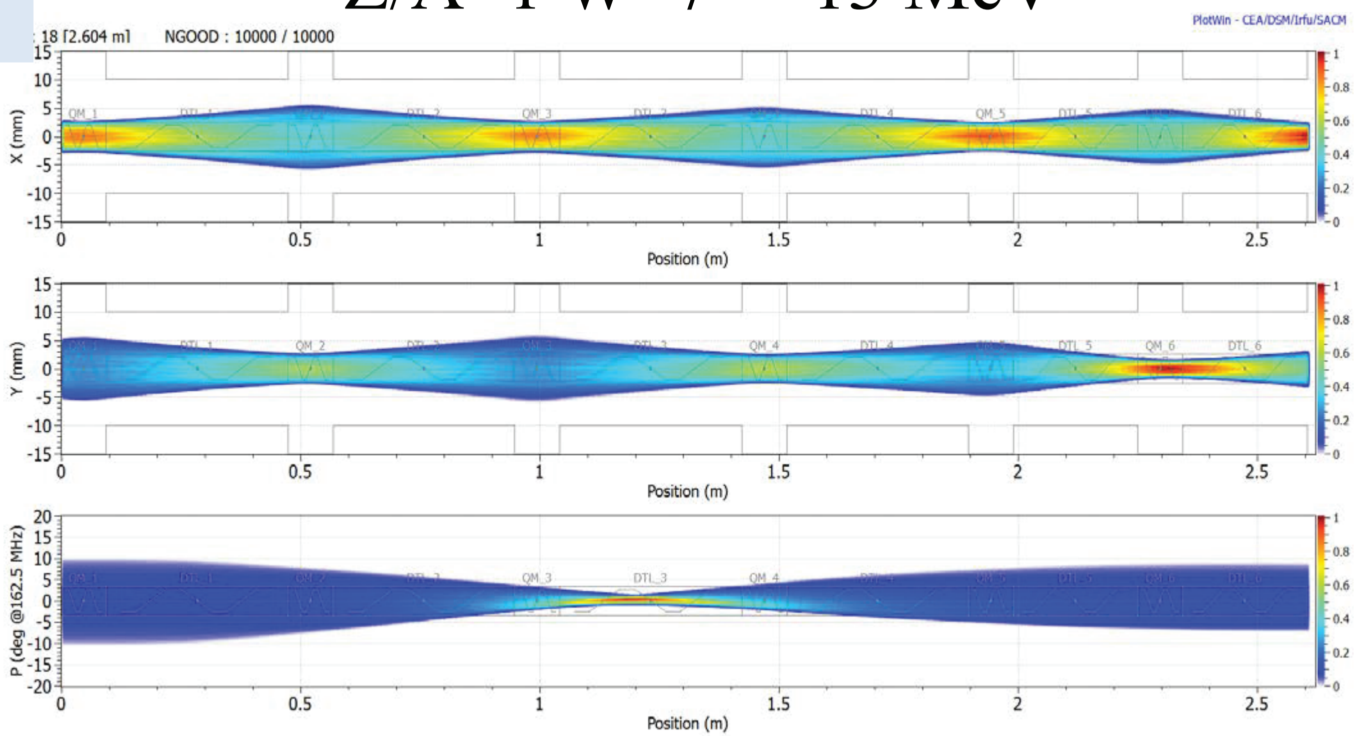
(предварительные оценки)



- A/Z=1,2,3;
- W(A/Z=1)=7 ÷13 MeV/n;
- W(A/Z=2,3)=7 ÷7 MeV/n;
- f=162.5 MHz;
- E_{smax}=1.8 Kp;
- Transmission=100%;



Z/A=1 W=7 - 13 MeV



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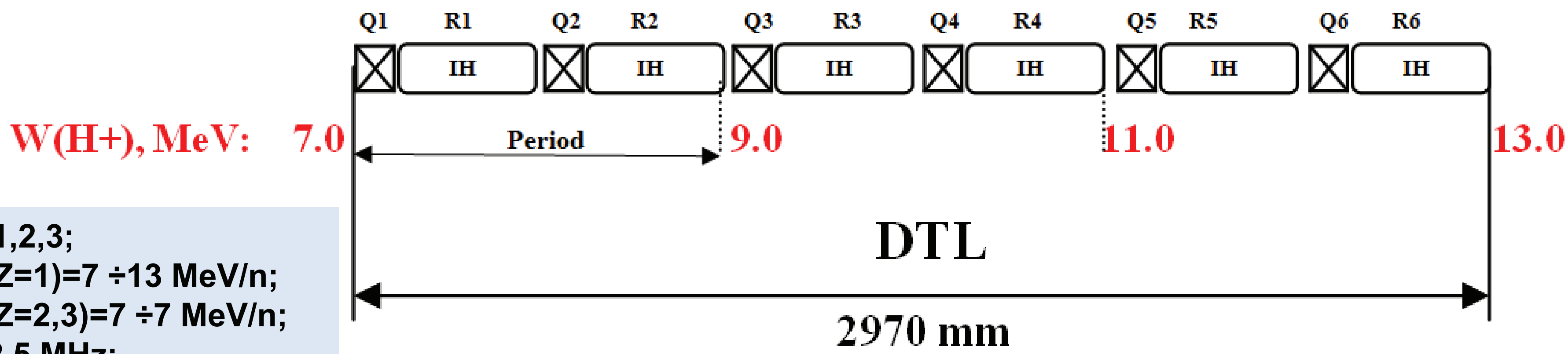

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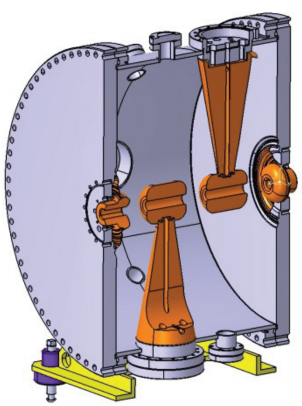
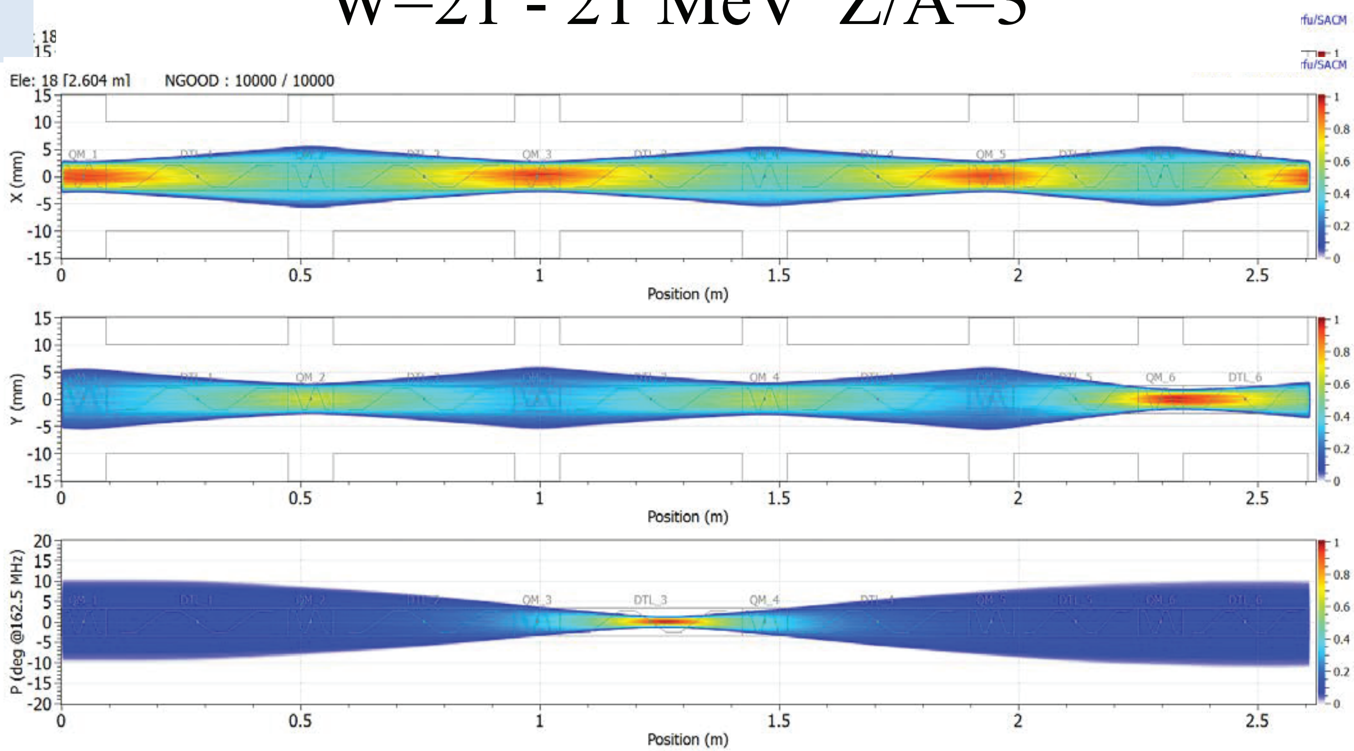
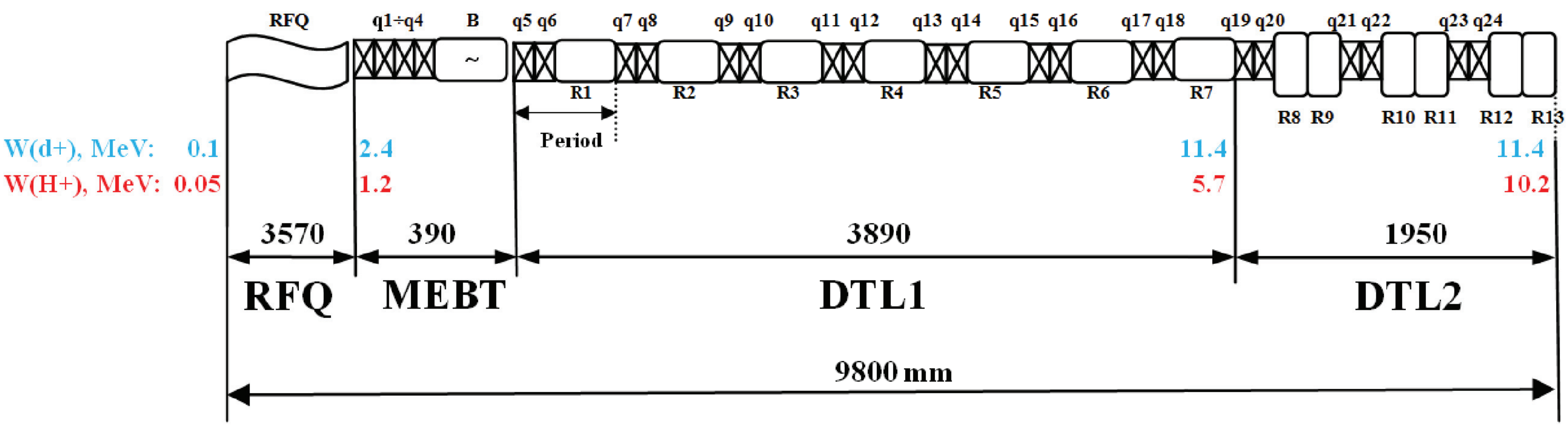
- Transmission=100%;

W=21 - 21 MeV Z/A=3





Nuclotron-based Ion Collider fAcility (NICA)



банчер ~

магнитная квадрупольная линза

5 зазорный резонатор

2 зазорный резонатор

Параметры	d+	H+
Нормализованный эмиттанс пучка	2 π мм мрад	2 π мм мрад
Номинальный ток	10 мА	10 мА
Трансмиссия для номинального тока	> 90 %	> 90 %
Энергия частиц на входе ускорителя	0.1 МэВ	0.05 МэВ
Энергия частиц на выходе RFQ	2.4 МэВ	1.2 МэВ
Энергия частиц на выходе ускорителя	11.4 МэВ	10.2 МэВ
Длина RFQ & DTL	9.8 м	

“Small” powerful neutron generators

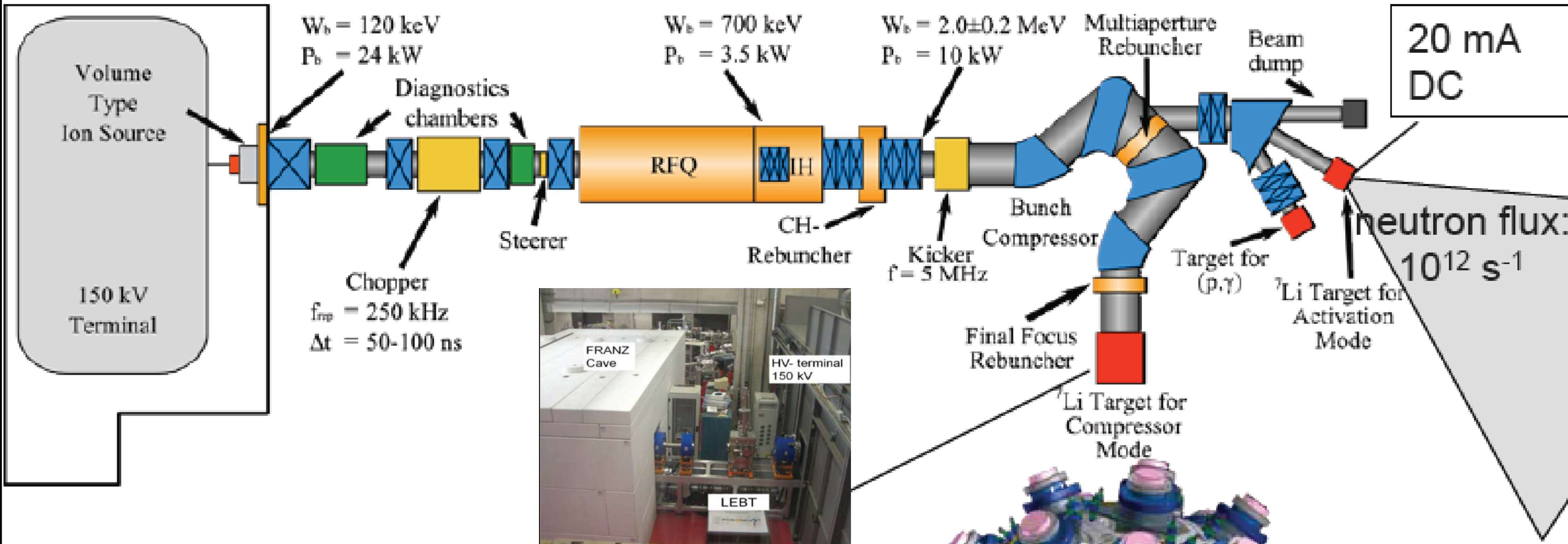
- **FRANZ** –
  the Frankfurt Neutron source at Stern-Gerlach-Zentrum

- **SARAF** –
  Soreq Applied Research Accelerator Facility

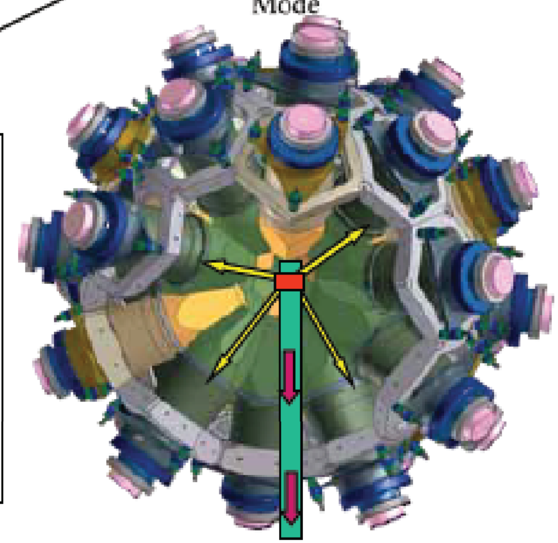
- **IFMIF** –
  International Fusion Materials Irradiation Facility

EVEDA –
Engineering Validation and Engineering Design Activities ->
prototype for IFMIF

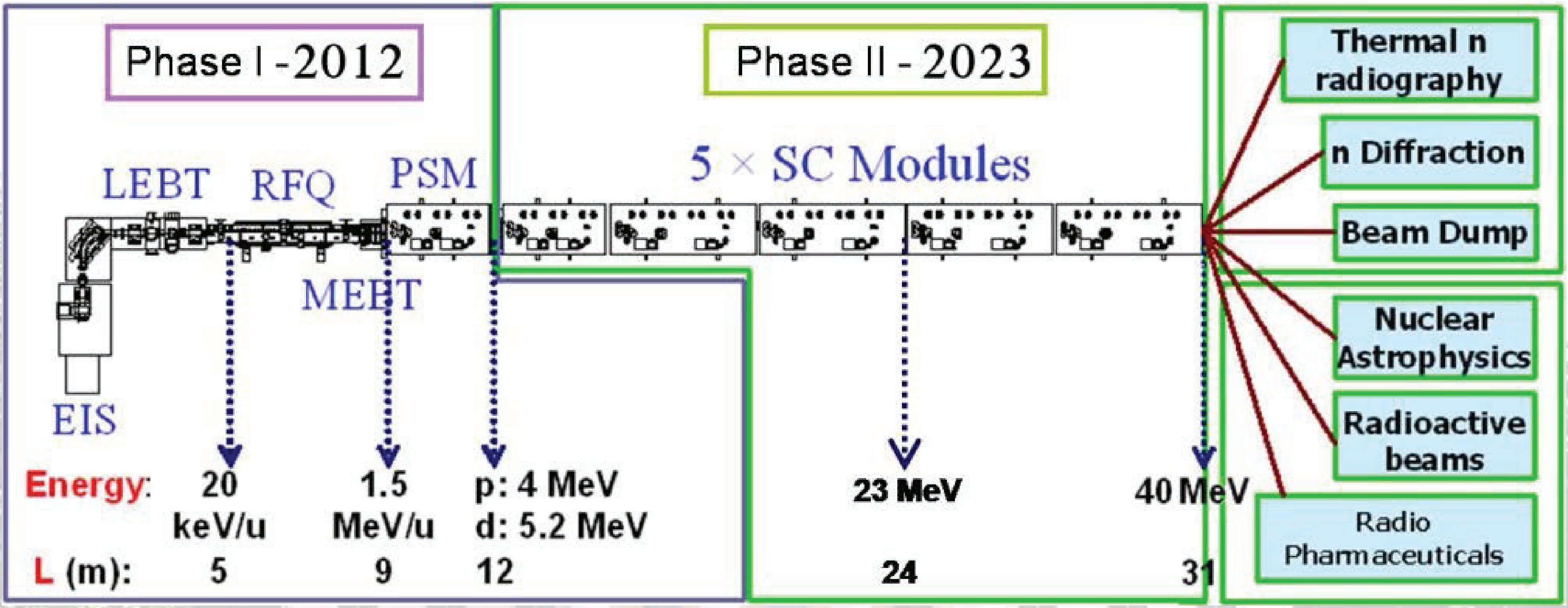
The Frankfurt neutron source at the Stern-Gerlach-Zentrum (FRANZ)

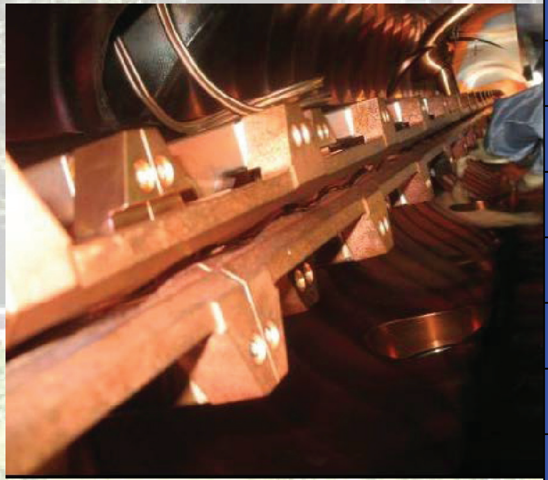


2 mA proton beam (8 A peak current)
250 kHz
< 1ns pulse width
neutron flux at 1 m: 10^7 s^{-1} cm^{-2}
neutron flux at 0.1m: 10^9 s^{-1} cm^{-2}



SARAF, Soreq, Palmachim and Yavne, Israel

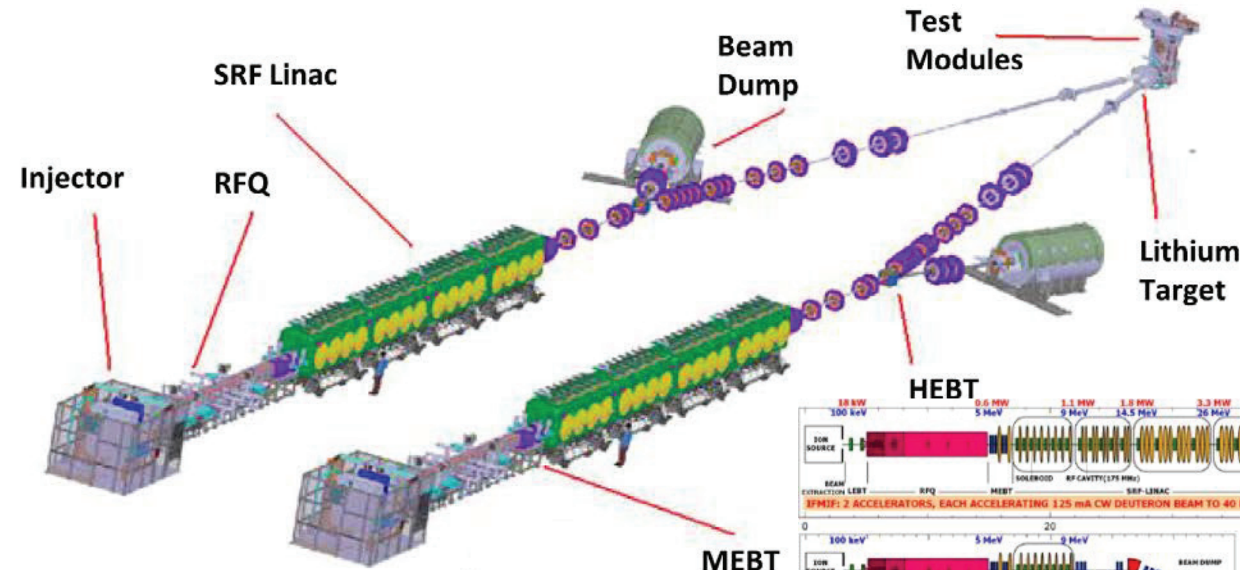


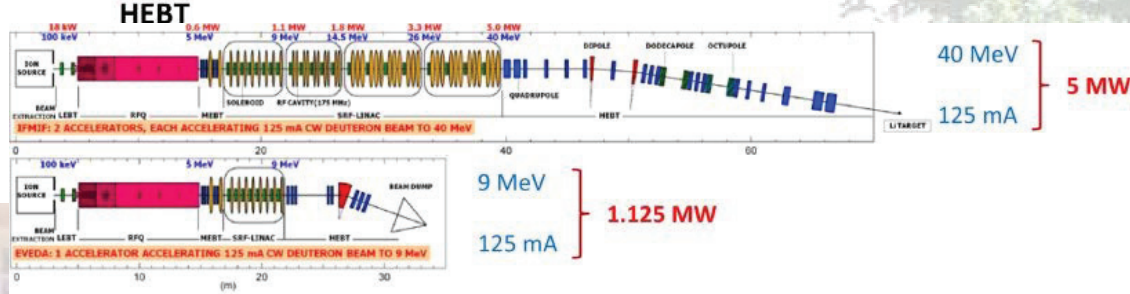


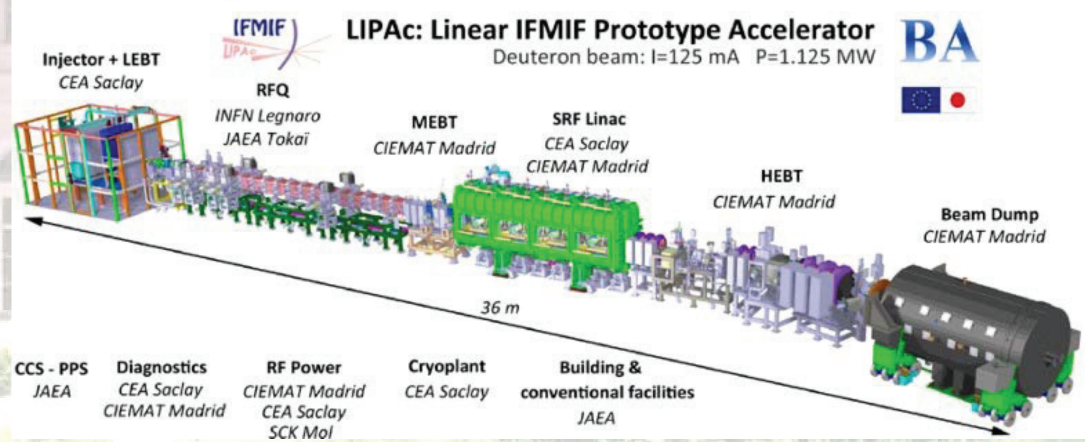
The SARAF Main Characteristics		
Parametr	Value	Unit
Ion species	P, d	
Maximum energy	40 (d), 35 (p)	MeV
Maximum current	5	mA
Duty cycle	100	%
Pulsed beam width	0.1-1	Ms
Pulsed beam repetiotion rate	0.1-10	Hz

http://soreq.gov.il

The International Fusion Materials Irradiation Facility (IFMIF), Rokkasho, Japan





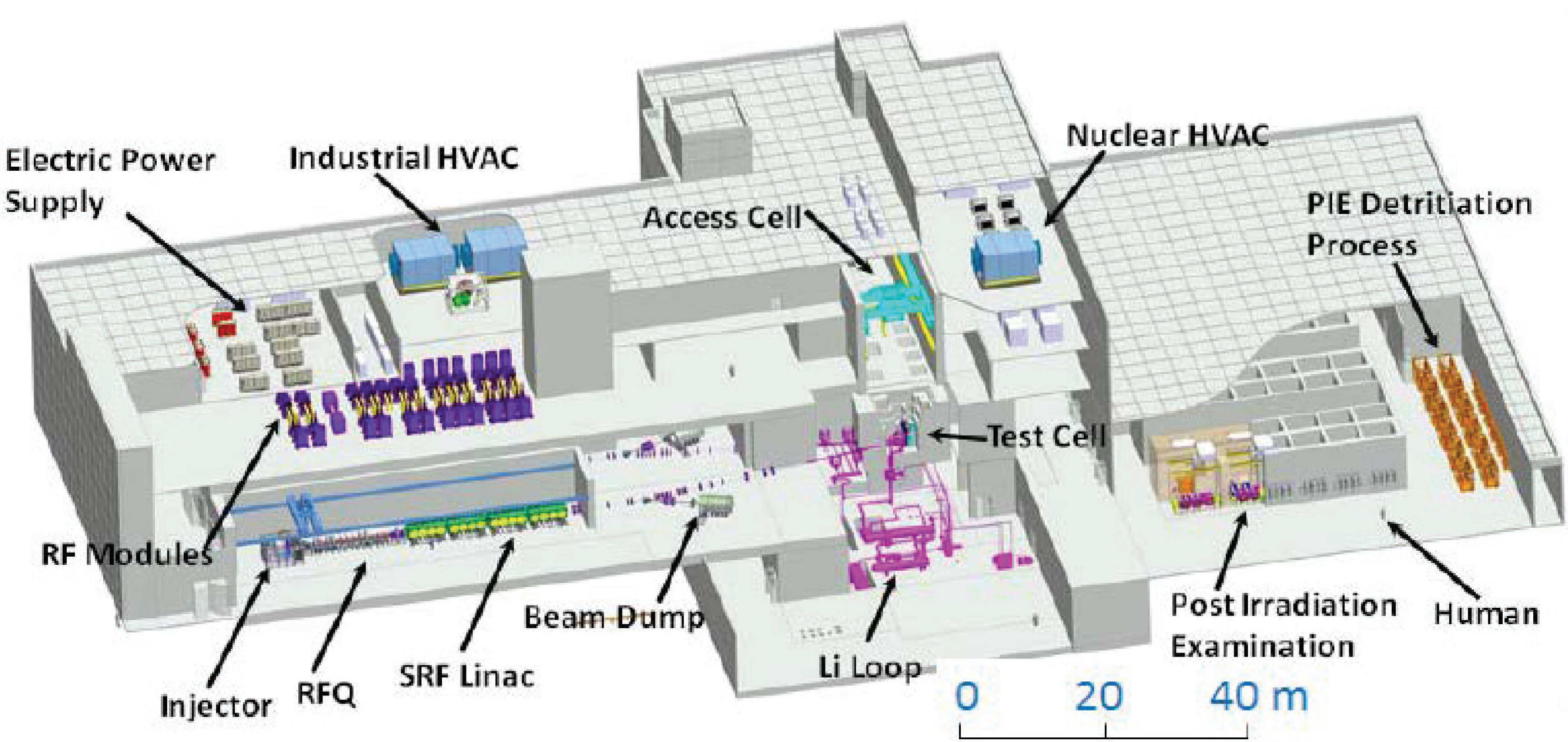


The IFMIF Main Characteristics		
Parameter	Value	Unit
Particle	d	
Output energy	9; 40	MeV
Current	125	mA
RFQ frequency	175	MHz
RFQ input energy	100	keV
RFQ output energy	5	MeV
RFQ length	9.8	m
RF power	1.2	MW

IFMIF RFQ MODULE CHARACTERIZATION VIA MECHANICAL AND RF MEASUREMENTS, Luigi Ferrari et.al., LINAC2016, THPLR050
TOWARDS COMMISSIONING OF THE IFMIF RFQ, A. Pisent , LINAC2016

The IFMIF/EVEDA EU-JA Project

- IFMIF: International Fusion Materials Irradiation Facility -> intense flux of 14MeV neutrons for material characterization (2 CW linacs, 125mA deuterons, 40MeV, lithium target)



- EVEDA: Engineering Validation and Engineering Design Activities -> prototype for IFMIF (1 CW accelerator 125mA, 9MeV)

The IFMIF/EVEDA EU-JA Project

Summer
2018
Beam test